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AN ANALYSIS OF  
A CHARRING ABLATION  
THERMAL PROTECTION SYSTEM

by Donald M. Curry

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20060516194

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1965

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SUMMARY

An analytical model is presented for predicting the transient one-dimensional thermal performance of a charring-ablator heat-protection system when exposed to a hyperthermal environment. The heat-protection system is considered to consist of an ablation material and backup structure. The ablating material is further considered to consist of three distinct regions or zones: char, reacting, and virgin material.

A FORTRAN IV digital computer program (STAB II) utilizing an implicit finite difference formulation has been written for the IBM 7094/40 computer system. The program considers one ablating material and a maximum of 12 backup materials with conduction or radiation and/or convection allowed between materials. Thermal properties of all materials are temperature dependent, with the properties of the charring material also being state dependent.

The governing differential equations and their implicit finite difference formulation are presented. The program input and output are described in detail. The FORTRAN program statements and nomenclature are presented. Also, the theoretical and experimental results are compared.] end

INTRODUCTION

The analysis and design of thermal protection systems for entry into an atmospheric environment have resulted in a voluminous amount of literature on the general subject of ablation. (See refs. 1 and 2 for a survey of information on ablation.) The ablation materials may generally be classified into three categories: subliming, melting and vaporizing, and charring. The charring ablator normally provides the most efficient thermal-protection shield for the major portion of a manned entry vehicle. This report describes a method for predicting the thermal response of a typical charring-ablation material. The response of a charring material to a hyperthermal environment is extremely complex, and the mathematical model presented to analyze the transient behavior of the material contains simplifying assumptions and approximations necessary to afford even a numerical solution.] end

The equations derived in this analysis have been programmed in FORTRAN IV for an IBM 7094/40 computer system. The numerical formulation of this digital program, designated STAB II, is such that an implicit solution is obtained. The thermal response of a typical charring material as predicted by STAB II is compared with arc tunnel results.

A sample problem is presented in appendix A. Program usage instructions, including definitions of the input terminology, are presented in appendix B. Appendixes C and D are the program FORTRAN IV statements and definitions of the program terminology. A general flow chart of the program is presented in appendix E.

#### SYMBOLS

A	collision frequency
$c_p$	specific heat
E	activation energy
F	exterior view factor
$F_{env}$	view factor-emissivity product to cabin environment
$H_d$	heat of virgin material degradation
$H_T$	total enthalpy
$H_w$	wall enthalpy
$H_{300}$	enthalpy of air at 300° K
h	film coefficient between backup materials
$h_{env}$	film coefficient between last backup material and cabin environment
k	thermal conductivity
$\dot{m}_c$	mass loss rate of char material
$\dot{m}_g$	gas ablation rate
NP	number of nodes in ablation material

$n$	order of reaction
$Q_{in.}$	net heat rate into front surface
$\dot{q}_c$ blow	hot wall convective heat flux with blowing
$\dot{q}_{comb}$	heat flux due to combustion
$\dot{q}_{cw}$	cold wall convective heat flux without blowing
$\dot{q}_{rad}$	radiation heat flux
$R$	universal gas constant
$S$	surface recession depth
$\dot{S}$	surface recession rate
$T$	temperature of node at beginning of time step
$T_{env}$	cabin environment temperature
$T'$	temperature of node at end of time step
$T_\infty$	radiation heat sink temperature
$VL$	thickness of ablation material
$X$	distance from surface to any point
$\Delta H_c$	heat of combustion per unit weight of char
$\Delta X$	thickness of a node
$\Delta\theta$	time step ( $\theta' - \theta$ )
$\epsilon$	emissivity of material
$\eta$	transpiration cooling efficiency
$\theta$	initial time
$\theta'$	final time
$\xi$	transform for the ablation material

$\rho$  density  
 $\sigma$  Stefan-Boltzmann constant  
 $\psi$  blocking effectiveness function

Subscripts:

c charred state  
i node number  
j material number  
v virgin state

#### PROGRAM DESCRIPTION

The following general requirements were established before writing a digital computer program to analyze a charring ablation system:

- (1) Stability of the equations for all applications.
- (2) Machine running time short enough to make use of the program economically feasible (a minimum of turn around time per problem).
- (3) A minimum of input per problem.
- (4) A wide variety of boundary conditions for application to both trajectory data and ground or flight test data analysis.

STAB II has been formulated in FORTRAN IV to analyze the transient thermal performance of a charring ablator heat protection system. The program considers one ablating material and up to 12 different backup materials with or without air gaps. Pure conduction or radiation and/or convection between backup materials is allowed. The ablation material may be divided into a maximum of 50 nodes, and each backup material may be subdivided into a maximum of 10 nodes. The thermal properties of the materials are in tabular form and are temperature dependent. The ablation material is also dependent upon its state, that is, fully charred, partially charred, et cetera.

The following surface boundary condition options are provided:

- (1) Cold-wall convective and radiative heat flux tables as a function of time. These components are specified separately, since mass transfer at the surface blocks part of the convective heating but, in general, has no effect on the radiant heating.

(2) Surface temperature as a function of time.

(3) Surface recession as a function of temperature or time. Surface recession as a function of temperature and pressure is also available.

Heat loss to the interior environment for the last node of the backup structure can be specified by two methods:

(1) Conduction into the node and radiation and/or convection loss to the interior environment.

(2) Conduction into the node and adiabatic wall.

The STAB II numerical formulation of the equations describing the response of the heat shield is such that an implicit solution has been obtained. It is well known that numerical solutions of partial differential equations are subject to several different types of errors. The first of these is the truncation error, due to the use of a finite subdivision. This error may be reduced by simply choosing a smaller subdivision,  $\Delta X$ . The exact values are approached more and more closely as  $\Delta X$  decreases. The second kind of error is the numerical, or roundoff error. The way in which this numerical error grows or decays with time determines the stability of the difference equations.

To illustrate the differences in the explicit and implicit equation form, consider a nonablating homogeneous solid. The one-dimensional Fourier conduction equation, neglecting any heat generation terms, is

$$\frac{\partial}{\partial X} \left( k \frac{\partial T}{\partial X} \right) = \rho c_p \frac{\partial T}{\partial \theta} \quad (1)$$

The finite difference form of equation (1) written in the conventional forward time step or explicit form for the  $i^{\text{th}}$  node is

$$\frac{\left( T_{i-1} - T_i \right)}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} - \frac{\left( T_i - T_{i+1} \right)}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X (T'_i - T_i)}{\Delta \theta} \quad (2)$$

where the prime superscript denotes values at the end of the time step

$$\Delta \theta = \theta' - \theta$$

For explicit conduction solutions, the following stability criterion has been established:

$$\frac{\rho c_p}{k} \frac{(\Delta X)^2}{\Delta \theta} \geq 2$$

which places an upper limit on the time step  $\Delta\theta$  for a fixed truncation error. This criterion can require a prohibitive amount of machine time.

Liebmann (ref. 3) advocated a solution of the equation which does not require this stability criterion. The finite difference equations are written in a backward time step form which affords an implicit solution.

The implicit (backward time step) difference form of equation (1) for the  $i^{th}$  node is:

$$\frac{\left(T'_{i-1} - T'_i\right)}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} - \frac{\left(T'_i - T'_{i+1}\right)}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} = \rho c_p \frac{\Delta X \left(T'_i - T_i\right)}{\Delta\theta} \quad (3)$$

Equation (3) uses the temperature differences at the end of the finite time interval instead of the beginning, as in the explicit method of equation (2). The only known temperature in equation (3) is  $T_i$ , but there are corresponding equations for each point in the system, and all are solved simultaneously to yield the temperature at each node.

Collecting all unknown temperatures on the left side of the equation and the known temperature on the right side, equation (3) becomes

$$\left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}}\right)T'_{i-1} - \left(\frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right. \\ \left. + \frac{\rho_i c_p i}{\Delta\theta}\right)T'_i + \left(\frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}}\right)T'_{i+1} = -\left(\frac{\rho_i c_p i}{\Delta\theta}\right)T_i \quad (4)$$

Equation (4) is of the form

$$AT'_{i-1} + BT'_i + CT'_{i+1} = D \quad (5)$$

STAB II generates such an equation for each node in the system.

Since radiation is an important mode of heat transfer in charring ablative systems, a problem is encountered in any equation containing a radiation term. The radiation heat flux, written in a backward difference form is:

$$\dot{q}_{rad} = F\epsilon\sigma \left(T_i^4 - T_\infty^4\right) \quad (6)$$

This term cannot be used in an implicit solution since the unknown temperature  $T_i'$  is to be the 4th power. The 4th power unknown can be eliminated by the following linearizations:

$$\left(T_i'\right)^4 = \left(T_i + \Delta T\right)^4 = T_i^4 \left(1 + \frac{\Delta T}{T_i}\right)^4 \quad (7)$$

where

$$\Delta T = T_i' - T_i$$

let

$$Z \equiv \frac{\Delta T}{T_i}$$

and rewrite equation (7) as

$$\left(T_i'\right)^4 = \left(T_i\right)^4 (1 + Z)^4 \quad (8)$$

If  $Z$  has an absolute value near zero, the following is true

$$(1 + Z)^4 \cong 1 + 4Z \quad (9)$$

Now substituting equation (9) into equation (8)

$$\begin{aligned} \left(T_i'\right)^4 &\cong \left(T_i\right)^4 (1 + 4Z) = \left(T_i\right)^4 \left(1 + 4 \frac{\Delta T}{T_i}\right) \\ &\cong 4T_i^3 T_i' - 3T_i^4 \end{aligned} \quad (10)$$

Equation (10) is a linearized approximation of equation (7) in which the unknown temperature is only to the first power. The assumption in equation (10) is that  $\Delta T/T_i$  has an absolute value near zero. Figure 1 is a plot of the error obtained when  $(1 + 4Z)$  is substituted for  $(1 + Z)^4$ . For most ablation problems in which the surface temperature is high and the radiation losses are significant, the value of  $\Delta T/T_i$  can easily be controlled to values of less than  $\pm 0.1$ .

Therefore, equation (6) can now be written

$$\dot{q}_{rad} = F\epsilon\sigma \left( 4T_i^3 T_i' - 3T_i^4 - T_\infty^4 \right) \quad (11)$$

Using the linearized approximation for the radiation terms, the resulting system of implicit difference equations constitute a tridiagonal matrix of the following form:

$$\begin{aligned}
 B_1 T_1 + C_1 T_2 &= D_1 \\
 A_2 T_1 + B_2 T_2 + C_2 T_3 &= D_2 \\
 A_3 T_2 + B_3 T_3 + C_3 T_4 &= D_3 \\
 \vdots &\quad \vdots & \vdots \\
 A_N T_{N-1} + B_N T_N &= D_N
 \end{aligned}$$

Gauss' elimination method, discussed in reference 4, is applied to solve the system of equations. This method affords a fast and accurate solution for matrices containing a dominant diagonal. The solution of this matrix gives the temperature of each node in the system for the next future time step. The entire process is repeated for each time step throughout the run, giving a time history of the temperature at each node.

Using this method of solution, residual errors in the temperature computations at the beginning of the time step are distributed throughout the entire system of nodal equations and tend to cancel out rapidly. The principal advantage in using the implicit method is a set of equations that are mathematically stable in time and distance. Therefore, the magnitude of the time step is not limited by a convergence criterion. However, care must be taken in selecting the magnitude of the time step in order to minimize truncation errors when the second derivative of temperature with respect to time is large. A similar approach is used to minimize truncation errors in distance by choosing small node dimensions in locations where large second derivatives of temperature with respect to distance are expected.

In the case of a char-forming ablative heat shield where approximately 80 percent of the heat is reradiated, instability can arise in taking large time steps. The temperature of the surface node can start oscillating on successive time steps when a balance between the radiation source and the heat sink has been achieved. Therefore, in ablation problems in which the surface node loses a large percentage of heat by radiation, oscillations of the node can be damped out by taking small time steps during conditions of high heat flux and near radiation equilibrium temperatures.

#### ANALYSIS

Figure 2 is a schematic of the thermal protection system to be analyzed. A receding surface has been assumed with the formation of a residual char layer and reaction zone. The thermal protection system is composed of one charring material and a maximum of 12 different backup materials with or without air gaps.

The analysis is such that the entire system may be composed of noncharring materials. The thermal properties of all materials are temperature dependent; also, the charring material properties are state dependent (fully or partially charred).

The response of charring ablation heat shields to a hyperthermal environment is extremely complex, and simplifying assumptions and approximations are necessary to afford a numerical solution. The following assumptions and approximations are utilized in the equations developed in this report:

(1) The material decomposes from the virgin state to a porous char layer in the reaction zone.

(2) The reaction zone can be defined by an upper and lower temperature limit.

(3) The gas generated within the reaction zone is assumed to pass out of the structure with no pressure loss. No gas accumulation within a node is allowed.

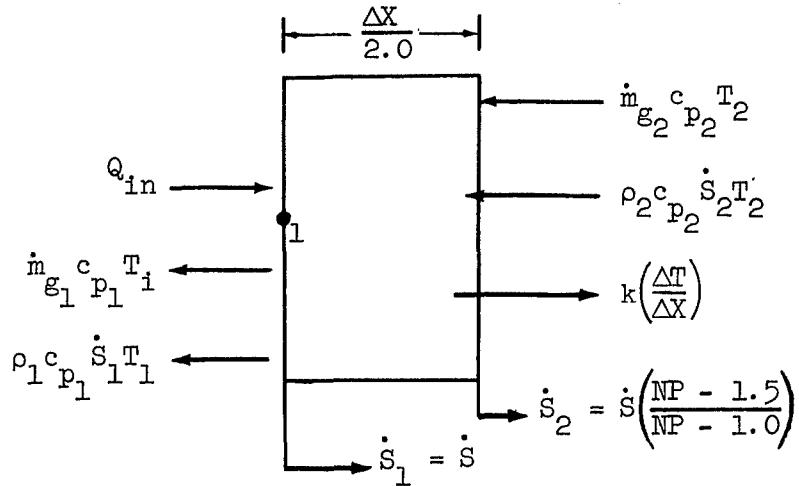
(4) Local thermal equilibrium is maintained between the gas and porous char matrix.

(5) The gas undergoes no further chemical reaction within the residual material after having been formed.

#### Derivation of Equations

The equations are derived for a moving boundary coordinate system, where the front face is the moving surface (ref. 5). With this system, the ablating material is divided into a fixed number of nodes of thickness  $\Delta X$  which depends on the instantaneous location of the front face. The surface recession is handled in a continuous manner, eliminating the need of throwing away or lumping off of nodes.

The physical model for the front surface, including all heating terms, is shown as follows:



The energy equation at the front char surface is

$$\begin{aligned}
 \frac{d}{d\theta} \left( \frac{1}{2} \Delta X \rho_1 c_{p_1} T_1 \right) &= \frac{1}{2} \Delta X \rho_1 c_{p_1} \frac{dT_1}{d\theta} + \frac{1}{2} \rho_1 c_{p_1} T_1 \frac{d(\Delta X)}{d\theta} \\
 &= Q_{in} + \dot{m}_{g_2} c_{p_2} T'_2 + \rho_2 \dot{S}_2 c_{p_2} T'_2 - \dot{m}_{g_1} c_{p_1} T'_1 \\
 &\quad - \rho_1 c_{p_1} \dot{S}_1 T'_1 - k_{l-2} \left( \frac{\Delta T}{\Delta X} \right) \tag{12}
 \end{aligned}$$

where

$$Q_{in} = \dot{q}_{c, \text{blow}} + \dot{q}_{rad} + \dot{q}_{comb} - F \epsilon \sigma \left( T_1^4 - T_\infty^4 \right)$$

and

$$\frac{d(\Delta X)}{d\theta} = \frac{d}{d\theta} \left( \frac{VL - S}{NP - 1} \right) = - \frac{\dot{S}}{NP - 1}$$

where  $S$  is the linear surface recession rate and  $NP$  is the total number of nodes in the ablation material of thickness  $VL$ .

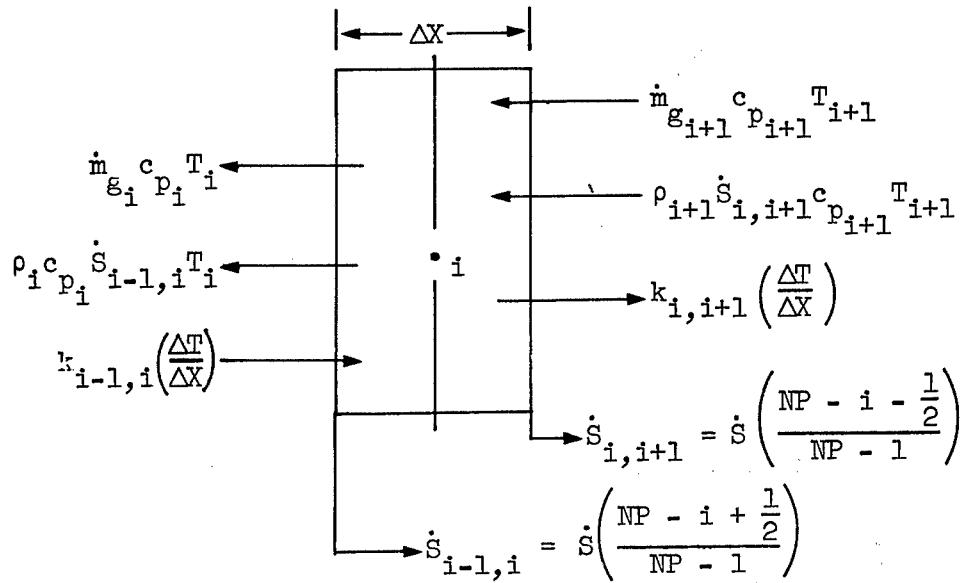
Rewriting equation (12) in implicit finite difference form

$$\begin{aligned}
 Q_{in} + \dot{m}_{g_2} c_{p_2} T'_2 - \dot{m}_{g_1} c_{p_1} T'_1 - \dot{s} \rho_1 c_{p_1} T'_1 - \frac{(T'_1 - T'_2)}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} \\
 + \rho_2 c_{p_2} \dot{s} \left( \frac{NP - 1.5}{NP - 1.0} \right) T'_2 = \rho_1 c_{p_1} \frac{\Delta X}{2} \left( \frac{T'_1 - T_1}{\Delta \theta} \right) \\
 - \frac{1}{2} \rho_1 c_{p_1} T'_1 \left( \frac{\dot{s}}{NP - 1} \right)
 \end{aligned} \tag{12a}$$

Then, rearranging and collecting terms yield

$$\begin{aligned}
 & - \left[ \dot{m}_{g_1} c_{p_1} + \dot{s} \rho_1 c_{p_1} + \rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} - \frac{1}{2} \rho_1 c_{p_1} \left( \frac{\dot{s}}{NP - 1} \right) \right] T'_1 \\
 & + \left[ \dot{m}_{g_2} c_{p_2} + \frac{1}{\frac{\Delta X}{2k_1} + \frac{\Delta X}{2k_2}} + \rho_2 c_{p_2} \dot{s} \left( \frac{NP - 1.5}{NP - 1.0} \right) \right] T'_2 \\
 & = -\rho_1 c_{p_1} \frac{\Delta X}{2\Delta\theta} T_1 - Q_{in.}
 \end{aligned} \tag{12b}$$

The physical model for interior points in the mature char zone, including all heating terms, is shown in the following sketch:



The energy equation for interior points in the char matrix is

$$\begin{aligned}
 \frac{d}{d\theta} \left( \Delta X_i \rho_i c_{p_i} T_i \right) &= \Delta X \rho_i c_{p_i} \frac{dT'_i}{d\theta} - \rho_i c_{p_i} T'_i \left( \frac{\dot{S}}{NP - 1} \right) \\
 &= \dot{m}_g_{i+1} c_{p_{i+1}} T'_{i+1} + k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T'_{i+1} \\
 &\quad - k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_g_i c_{p_i} T'_i - \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T'_i \quad (13)
 \end{aligned}$$

Putting equation (13) in an implicit finite difference form yields

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[ \dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right. \\
 & \quad \left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left( \frac{\dot{S}}{NP - 1} \right) \right] T'_i \\
 & + \left[ \dot{m}_{g_{i+1}} c_{p_{i+1}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} \\
 & = -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i
 \end{aligned}$$

(13a)

In the mature char zone, no internal gaseous ablation products are assumed to form. The reaction zone is the source for the formation of the internal gaseous products. Therefore, in equations (12) and (13),  $\dot{m}_{g_i} = \dot{m}_{g_{i+1}}$

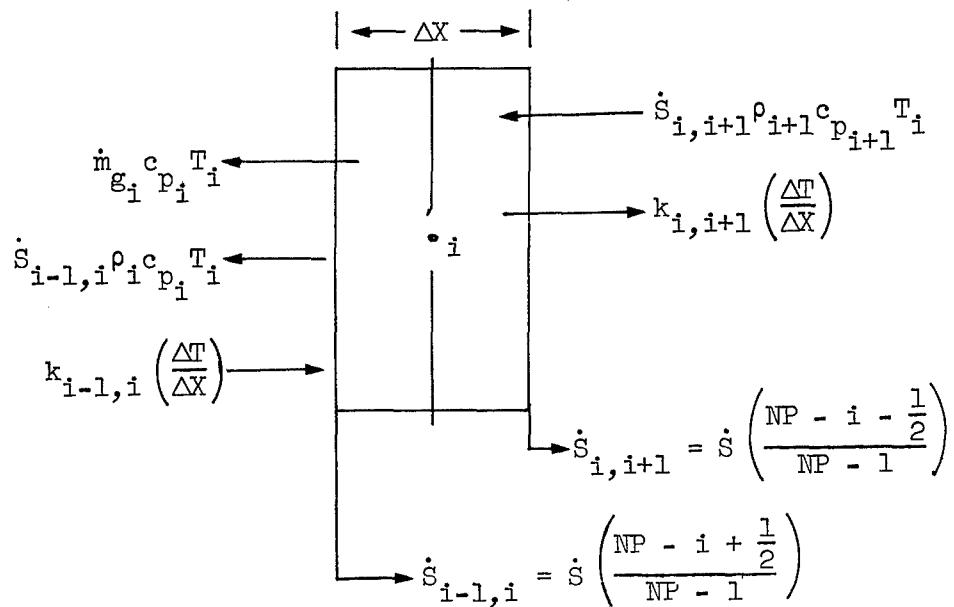
The physical model for nodes in the reaction zone is identical to schematic shown for the interior nodes in the char except for considering the energy absorbed in formation of the gaseous ablation products. The heat balance equation for a node in the reaction zone is

$$\begin{aligned}
 \frac{d}{d\theta} (\Delta X \rho_i c_{p_i} T_i) &= \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T'_i \left( \frac{\dot{S}}{NP - 1} \right) - \left( \dot{m}_{g_i} - \dot{m}_{g_{i+1}} \right) H_d \\
 &= \dot{m}_{g_{i+1}} c_{p_{i+1}} T'_{i+1} + k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T'_{i+1} \\
 &\quad - k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_{g_i} c_{p_i} T'_i - \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T'_i \quad (14)
 \end{aligned}$$

Rearranging,

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[ \dot{m}_{g_i} c_{p_i} + \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right. \\
 & \quad \left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left( \frac{\dot{S}}{NP - 1} \right) \right] T'_i + \left[ \dot{m}_{g_{i+1}} c_{p_{i+1}} \right. \\
 & \quad \left. + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} \\
 & = -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i - \left( \dot{m}_{g_i} - \dot{m}_{g_{i+1}} \right) H_d \quad (14a)
 \end{aligned}$$

The physical model for the interface between the reaction zone and virgin material is illustrated as follows:



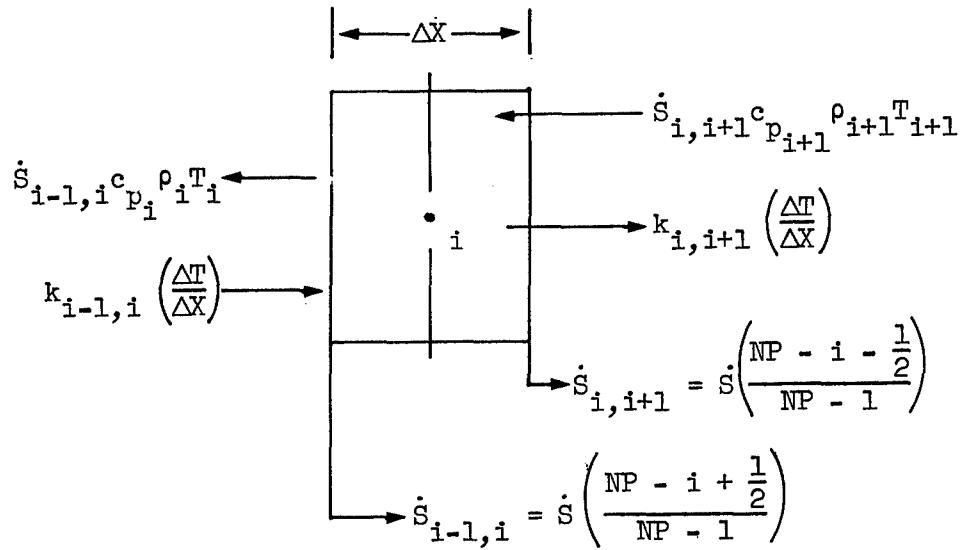
The heat balance equation for this node is

$$\begin{aligned}
 \frac{d}{d\theta} \left( \Delta X \rho_i c_{p_i} T'_i \right) &= \Delta X \rho_i c_{p_i} \frac{dT'_i}{d\theta} - \rho_i c_{p_i} T'_i \left( \frac{\dot{S}}{NP - 1} \right) - \dot{m}_g H_d \\
 &= k_{i-1, i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T'_{i+1} \\
 &\quad - k_{i, i+1} \left( \frac{\Delta T}{\Delta X} \right) - \dot{m}_g c_{p_i} T'_i - \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T'_i \tag{15}
 \end{aligned}$$

Rearranging yields

$$\begin{aligned}
 \left( \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[ \dot{m}_g c_{p_i} + \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} \right. \\
 \left. + \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} - \rho_i c_{p_i} \left( \frac{\dot{S}}{NP - 1} \right) \right] T'_i \\
 + \left[ \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} \\
 = -\rho_i c_{p_i} \frac{\Delta X}{\Delta \theta} T_i - \dot{m}_g H_d \tag{15a}
 \end{aligned}$$

The physical model for an interior node in the virgin material is



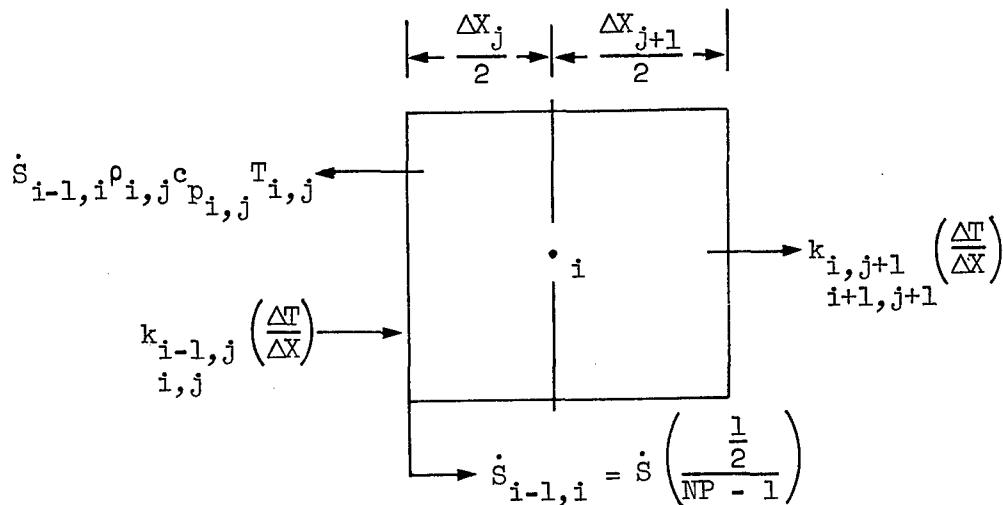
The heat balance for this nonablating node is

$$\begin{aligned}
 \frac{d}{d\theta} (\Delta X \rho_i c_{p_i} T_i) &= \Delta X \rho_i c_{p_i} \frac{dT_i}{d\theta} - \rho_i c_{p_i} T'_i \left( \frac{\dot{S}}{NP - 1} \right) \\
 &= k_{i-1,i} \left( \frac{\Delta T}{\Delta X} \right) + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) T'_{i+1} - k_{i,i+1} \left( \frac{\Delta T}{\Delta X} \right) \\
 &\quad - \rho_i c_{p_i} \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) T'_i \tag{16}
 \end{aligned}$$

Rearranging,

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} \right) T'_{i-1} - \left[ \frac{1}{\frac{\Delta X}{2k_{i-1}} + \frac{\Delta X}{2k_i}} + \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} \right. \\
 & \quad \left. + \rho_i c_p_i \dot{S} \left( \frac{NP - i + \frac{1}{2}}{NP - 1} \right) + \rho_i c_p_i \frac{\Delta X}{\Delta \theta} - \rho_i c_p_i \left( \frac{\dot{S}}{NP - 1} \right) \right] T'_i \\
 & + \left[ \frac{1}{\frac{\Delta X}{2k_i} + \frac{\Delta X}{2k_{i+1}}} + \rho_{i+1} c_{p_{i+1}} \dot{S} \left( \frac{NP - i - \frac{1}{2}}{NP - 1} \right) \right] T'_{i+1} = -\rho_i c_p_i \frac{\Delta X}{\Delta \theta} T_i \quad (16a)
 \end{aligned}$$

The physical model for the last node in the ablation material and first node in the backup structure is



For this interface,  $T'_{i,j} = T'_{i,j+1}$ .

The heat balance equation for this node is

$$\begin{aligned}
 & \frac{d}{d\theta} \left[ \left( \frac{\Delta X_j}{2} \rho_{i,j} c_{p_{i,j}} + \frac{\Delta X_{j+1}}{2} c_{p_{i,j+1}} \rho_{i,j+1} \right) T_i \right] \\
 &= \left( \frac{\Delta X_j \rho_{i,j} c_{p_{i,j}} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2} \right) \frac{dT_i}{d\theta} - \frac{1}{2} \left( \frac{\dot{S}}{NP - 1} \right) c_{p_{i,j}} \rho_{i,j} T'_i \\
 &= k_{i-1,j} \left( \frac{\Delta T}{\Delta X} \right) - c_{p_{i,j}} \rho_{i,j} \dot{S} \left( \frac{\frac{1}{2}}{NP - 1} \right) T'_i - k_{i,j+1} \left( \frac{\Delta T}{\Delta X} \right)
 \end{aligned} \tag{17}$$

Rearranging yields

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1} - \left[ \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right. \\
 & \quad \left. + \left( \frac{\Delta X_j \rho_{i,j} c_{p_{i,j}} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2\Delta\theta} \right) \right] T'_i + \left( \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) T'_{i+1} \\
 &= - \left( \frac{\Delta X_j c_{p_{i,j}} \rho_{i,j} + \Delta X_{j+1} c_{p_{i,j+1}} \rho_{i,j+1}}{2\Delta\theta} \right) T_i
 \end{aligned} \tag{17a}$$

The backup structure may contain up to a maximum of 12 different materials with or without air gaps between materials. Therefore, conduction or radiation and/or convection between materials is allowed. The heat balance equations for the various modes of heat transfer in the backup structure are presented in the following equations:

(1) Interior node material:

$$\frac{\left(\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j}\right)}{\frac{1}{2k_{i-1,j}} + \frac{1}{2k_{i,j}}} - \frac{\left(\frac{T'_{i,j} - T'_{i+1,j}}{\Delta X_j}\right)}{\frac{1}{2k_{i,j}} + \frac{1}{2k_{i+1,j}}} = \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} \left(T'_{i,j} - T_{i,j}\right) \quad (18)$$

Rearranging, equation (18) becomes

$$\begin{aligned} & \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}} \right. \\ & \quad \left. + \rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} \right) T'_{i,j} + \left( \frac{1}{\frac{\Delta X_j}{2k_{i,j}} + \frac{\Delta X_j}{2k_{i+1,j}}} \right) T'_{i+1,j} \\ & = -\rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} T_{i,j} \end{aligned} \quad (18a)$$

(2) First and last nodes of two interior materials with no gap:

$$\begin{aligned} & \frac{\left(\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j}\right)}{\frac{1}{2k_{i-1,j}} + \frac{1}{2k_{i,j}}} - \frac{\left(\frac{T'_{i,j+1} - T'_{i+1,j+1}}{\Delta X_{j+1}}\right)}{\frac{1}{2k_{i,j+1}} + \frac{1}{2k_{i+1,j+1}}} \\ & = \left( \frac{\rho_{i,j} c_{p_{i,j}} \frac{\Delta X_j}{\Delta \theta} + \rho_{i,j+1} c_{p_{i,j+1}} \frac{\Delta X_{j+1}}{\Delta \theta}}{2 \Delta \theta} \right) \left(T'_{i,j} - T_{i,j}\right) \end{aligned} \quad (19)$$

For this case,  $T'_{i,j} = T'_{i,j+1}$

Rearranging, equation (19) becomes

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left[ \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right. \\
 & \quad \left. + \left( \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + \rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} \right) \right] T'_{i,j} \\
 & \quad + \left( \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) T'_{i+1,j+1} \\
 & = - \left( \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j + c_{p_{i,j+1}} \rho_{i,j+1} \Delta X_{j+1}}{2 \Delta \theta} \right) T_{i,j}
 \end{aligned} \tag{19a}$$

(3) First node of interior material with an air gap between materials:

$$\begin{aligned}
 h_j (T'_{i-1,j} - T'_{i,j+1}) + \left( \frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \left( T'_{i-1,j} - T'_{i,j+1} \right) \\
 - \left( \frac{T'_{i,j+1} - T'_{i+1,j+1}}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) = \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} (T'_{i,j+1} - T_{i,j+1})
 \end{aligned} \tag{20}$$

Equation (20) may be linearized by using the approximation

$$T'^4 \cong 4T^3 T' - 3T^4$$

as discussed in the Program Description section.

Therefore, rearranging and linearizing, equation (20) becomes

$$\begin{aligned}
 & \left[ h_j + \left( \frac{4\sigma T_{i-1,j}^3}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right] T'_{i-1,j} - \left[ h_j + \left( \frac{4\sigma T_{i,j+1}^3}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right. \\
 & \quad \left. + \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} + \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} \right] T'_{i,j+1} \\
 & + \left( \frac{1}{\frac{\Delta X_{j+1}}{2k_{i,j+1}} + \frac{\Delta X_{j+1}}{2k_{i+1,j+1}}} \right) T'_{i+1,j+1} = - \frac{\rho_{i,j+1} c_{p_{i,j+1}} \Delta X_{j+1}}{2 \Delta \theta} T_{i,j+1} \\
 & \quad - \left( \frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \left( T_{i,j+1}^4 - T_{i-1,j}^4 \right) \quad (20a)
 \end{aligned}$$

(4) Last node of an interior material with an air gap between materials:

$$\begin{aligned}
 & \frac{\left( T'_{i-1,j} - T'_{i,j} \right)}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} - h_j \left( T'_{i,j} - T'_{i,j+1} \right) \\
 & - \left( \frac{\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \left( T_{i,j}^4 - T_{i,j+1}^4 \right) = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} \left( T'_{i,j} - T_{i,j} \right) \quad (21)
 \end{aligned}$$

Rearranging and linearizing, equation (21) becomes

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left[ h_j + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + \left( \frac{4\sigma T^3_{i,j}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right. \\
 & \quad \left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} \right] T'_{i,j} + \left[ h_j + \left( \frac{4\sigma T^3_{i,j+1}}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \right] T'_{i,j+1} \\
 & = - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} T_{i,j} + \left( \frac{3\sigma}{\frac{1}{\epsilon_j} + \frac{1}{\epsilon_{j+1}} - 1} \right) \left( T^4_{i,j+1} - T^4_{i,j} \right)
 \end{aligned} \tag{21a}$$

(5) Final node in backup structure:

(a) Adiabatic surface -

$$\frac{\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j} + \frac{\Delta X_j}{2k_{i-1,j} + 2k_{i,j}}}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} = \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} (T'_{i,j} - T_{i,j}) \tag{22}$$

Rearranging, equation (22) becomes

$$\begin{aligned}
 & \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right. \\
 & \quad \left. + \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} \right) T'_{i,j} = - \frac{\rho_{i,j} c_{p_{i,j}} \Delta X_j}{2 \Delta \theta} T_{i,j}
 \end{aligned} \tag{22a}$$

(b) Radiation and/or convection loss to cabin environment -

$$\left( \frac{\frac{T'_{i-1,j} - T'_{i,j}}{\Delta X_j}}{\frac{1}{2k_{i-1,j}} + \frac{1}{2k_{i,j}}} \right) - h_{env} (T'_{i,j} - T_{env}) - F_{env} \sigma \left( T'_{i,j}^4 - T_{env}^4 \right) = \frac{\rho_{i,j} c p_{i,j} \Delta X_j}{2 \Delta \theta} (T'_{i,j} - T_{i,j}) \quad (23)$$

Rearranging, equation (23) becomes

$$\left( \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} \right) T'_{i-1,j} - \left( h_{env} + \frac{1}{\frac{\Delta X_j}{2k_{i-1,j}} + \frac{\Delta X_j}{2k_{i,j}}} + F_{env} \sigma \frac{4T_{i,j}^3}{\Delta \theta} \right. \\ \left. + \frac{\rho_{i,j} c p_{i,j} \Delta X_j}{2 \Delta \theta} \right) T'_{i,j} = - \frac{\rho_{i,j} c p_{i,j} \Delta X_j}{2 \Delta \theta} T_{i,j} - h_{env} T_{env} - F_{env} \sigma \left( 3T_{i,j}^4 + T_{env}^4 \right) \quad (23a)$$

#### Discussion of Assumptions

A brief discussion of several assumptions and approximations made in deriving the heat balance equations is now presented.

As shown in the Derivation of Equations section, transient heat conduction, thermal degradation, and the flow of the gaseous products from the reaction zone are the internal thermal transport phenomena of interest. Several methods are available in the treatment of the thermal decomposition process, and they differ primarily in whether the chemical decomposition occurs in a single plane at a fixed temperature or whether a spatially continuous decomposition in depth is assumed. This analysis assumes that the decomposition from the virgin to the char state occurs in a reaction zone that is defined by known temperature limits. These temperature limits are determined from thermogravimetric test data for the particular material being investigated. Figure 3 is a thermogravimetric curve for typical charring ablation material. From this curve, the rate of pyrolysis  $\dot{m}_g$  is calculated by knowing the

temperature change of a particular node with time, that is,

$$\dot{\rho}_i = \frac{\rho'_i - \rho_i}{\Delta\theta} \quad (24)$$

and

$$\dot{m}_{g_i} = \sum_i^N \dot{\rho}_i \Delta X_i \quad (25)$$

This method of computing the gas-generation rates and local instantaneous density may be subject to error since the thermogravimetric curve of a material is influenced by temperature rise rate (deg/sec), and the reaction zone may shift up and down the temperature scale. This error can be eliminated by the use of an Arrhenius expression of the form

$$\frac{d\rho}{d\theta} = -A(\rho - \rho_c)^n e^{-\frac{E}{RT}} \quad (26)$$

The method now being used in STAB II (equation (25)) to calculate the pyrolysis rate is being investigated to determine its validity. The final formulation of the pyrolysis rate law must rest heavily on the experimental rate data for the material under investigation. The use of simple expressions such as equations (24) and (25) may be entirely adequate, depending upon activation energy for the decomposition process and order of reaction.

The aerodynamic heating input in the analysis consists of convective and radiative components treated separately. This distinction is necessary since the convective heating can be significantly reduced as a result of the injection of the ablation gases into the boundary layer, with generally no effect on radiant heating. Reduction in the convective heating rate can be approximated by the following expression (ref. 6):

$$\dot{q}_{block} \equiv \eta \dot{m}_g (H_T - H_w) \quad (27)$$

Therefore,

$$\dot{q}_{c, blow} = \dot{q}_{cw} \left( \frac{H_T - H_w}{H_T - H_{300}} \right) - \dot{q}_{block} \quad (28)$$

However, equation (28) is unsatisfactory for high blowing rates, since  $\dot{q}_{block}$  can become greater than  $\dot{q}_{cw}$ . An experimental curve of blocking effectiveness  $\psi = \frac{\dot{q}_{c,blow}}{\dot{q}_{cw}}$  as a function of the mass transfer parameter  $\frac{\dot{m}_c H_c T}{\dot{q}_{cw}}$  can be employed to determine the heating reduction at high blowing rates. Both methods have been employed in the STAB II analysis. Equation (28) is presently in use. However, no satisfactory method for accurately predicting the convective heat blockage has been determined.

Another source of heating is the combustion of the ablation products in the boundary layer. Reference 7 presents an analysis of the oxidation of a carbon surface and the resulting combustive heating. The heating due to combustion as derived in reference 7 is

$$\dot{q}_{comb} = \dot{m}_c \Delta H_c \quad (29)$$

where  $\Delta H_c$  is the heat of combustion per unit weight of char.

The thermal properties of the ablation material are both temperature and state dependent (fully or partially charred). Figure 4 is an illustration of the variation of these properties with temperature and state. The thermal properties are assumed to vary as follows:

$$(1) \text{ Char zone } (T_i \geq T_{char})$$

$$k_c = f(\text{temp})$$

$$c_{p_c} = f(\text{temp})$$

$$\rho_c = \text{constant}$$

$$(2) \text{ Reaction zone } (T_{abl} \leq T_i < T_{char})$$

$$\rho = f(\text{temp}) = \rho_v + (\rho_v - \rho_c) \left( \frac{T_i - T_{abl}}{T_{abl} - T_{char}} \right)$$

$$k = f(\rho) = k_c + (k_v - k_c) \left( \frac{\rho_i - \rho_c}{\rho_v - \rho_c} \right)$$

$$c_p = f(\rho) = c_{p_c} + (c_{p_v} - c_{p_c}) \left( \frac{\rho_i - \rho_c}{\rho_v - \rho_c} \right)$$

(3) Virgin zone ( $T_i < T_{abl}$ )

$$\rho_v = \text{constant}$$

$$k_v = f(\text{temp})$$

$$c_{p_v} = f(\text{temp})$$

The calculation of char removal, due to chemical, thermal, or mechanical mechanism or a combination of these mechanisms, has been examined by a multitude of investigators and numerous correlations exist, depending on the specific material involved.

To provide a maximum degree of flexibility for analyzing both ground and flight test data and synthesizing trajectories, the following provisions for char removal (surface movement) are provided:

- (1) Removal of char as a function of surface temperature.
- (2) Removal of char at a rate which is a function of time.

As the char is removed, the surface moves with respect to a coordinate fixed in the material. The distance between the initial surface location and the char surface is

$$S = \int_0^\theta \dot{S} d\theta$$

#### ANALYSIS VERIFICATION

As discussed in the previous sections, approximations and assumptions were made in the analytical model to afford a quick and accurate solution in predicting the thermal response of a charring heat shield. These simplifying assumptions and approximations are expected to introduce only minor errors; however, the validity of the analyses and resultant accuracy can be judged only by a comparison with exact theoretical solutions and experimental data. Three examples have been selected, and a comparison of the STAB II results with the theoretical and test data is discussed in the following paragraphs.

An elementary transient heating example was chosen to demonstrate the accuracy and numerical stability of the STAB II program. A steel slab 6 inches thick was selected and assumed to be at uniform initial temperature of  $460^{\circ}\text{R}$  ( $0^{\circ}\text{F}$ ). The thermal properties were considered constant. The

front surface was subjected to a heating rate of  $72 \text{ Btu}/\text{ft}^2\text{-sec}$ , and an adiabatic back surface was assumed. Figure 5 shows a comparison of the STAB II calculated in-depth temperatures as a function of time with the exact solution taken from reference 8.

To demonstrate the STAB II solution with a moving boundary, a slab with constant properties, uniform initial temperature, front surface moving with a constant velocity, and constant surface temperature was chosen. The exact solution for a semi-infinite slab with these boundary and initial conditions is presented in reference 9. Figure 6 presents a comparison of the STAB II temperature response with the exact solutions. As can be seen from this figure, the two solutions are not in agreement for approximately the first 50 to 60 seconds of the transient. This disagreement is the result of the quasi-steady state assumption made in the exact solution analysis.

$$\left[ \left( \frac{\partial T}{\partial \theta} \right)_{\xi=0} = 0; k \left( \frac{\partial T}{\partial X} \right)_{X=0} = \dot{S} \rho c_p \Delta T \right]$$

A calculation was made to estimate the induction time (time at which  $\frac{\partial T}{\partial \theta} = 0$  is a good assumption) and found to be approximately 60 seconds, which is in agreement with the STAB II results.

Finally, to verify the fully charring ablation model, an example of a typical charring material was chosen. (See the sample problem in appendix A.) The charring ablation material is initially 1.6 inches thick with an adiabatic back surface and a constant heat flux of  $95 \text{ Btu}/\text{ft}^2\text{-sec}$  applied to the front surface. The surface is assumed to recede at a constant velocity of  $3.05 \times 10^{-3} \text{ in./sec}$ . Figure 7 presents a comparison of the in-depth temperatures with actual test results obtained in an arc tunnel. The results are in good agreement, with the largest deviations between calculated and measured values occurring for the thermocouple located at a depth of 1.0 inch. The disagreement could be attributed to several possible errors: thermal property values, incorrect location of thermocouples, et cetera. The effect of varying the thermal properties (thermal conductivity, specific heat, et cetera) is presently being investigated.

Tables I and II present the input and output data used for this example. Figures 8, 9, and 10 are the resulting plot routine output.

The comparisons between the computer results and the exact solutions and test results are considered satisfactory.

#### CONCLUDING REMARKS

An analysis and a computer program for predicting the transient thermal response of a charring ablation thermal protection system has been described. The numerical formulation of the equations is such that an implicit solution is obtained. This method of solution affords both a rapid and accurate solution for both ablating and nonablating type problems.

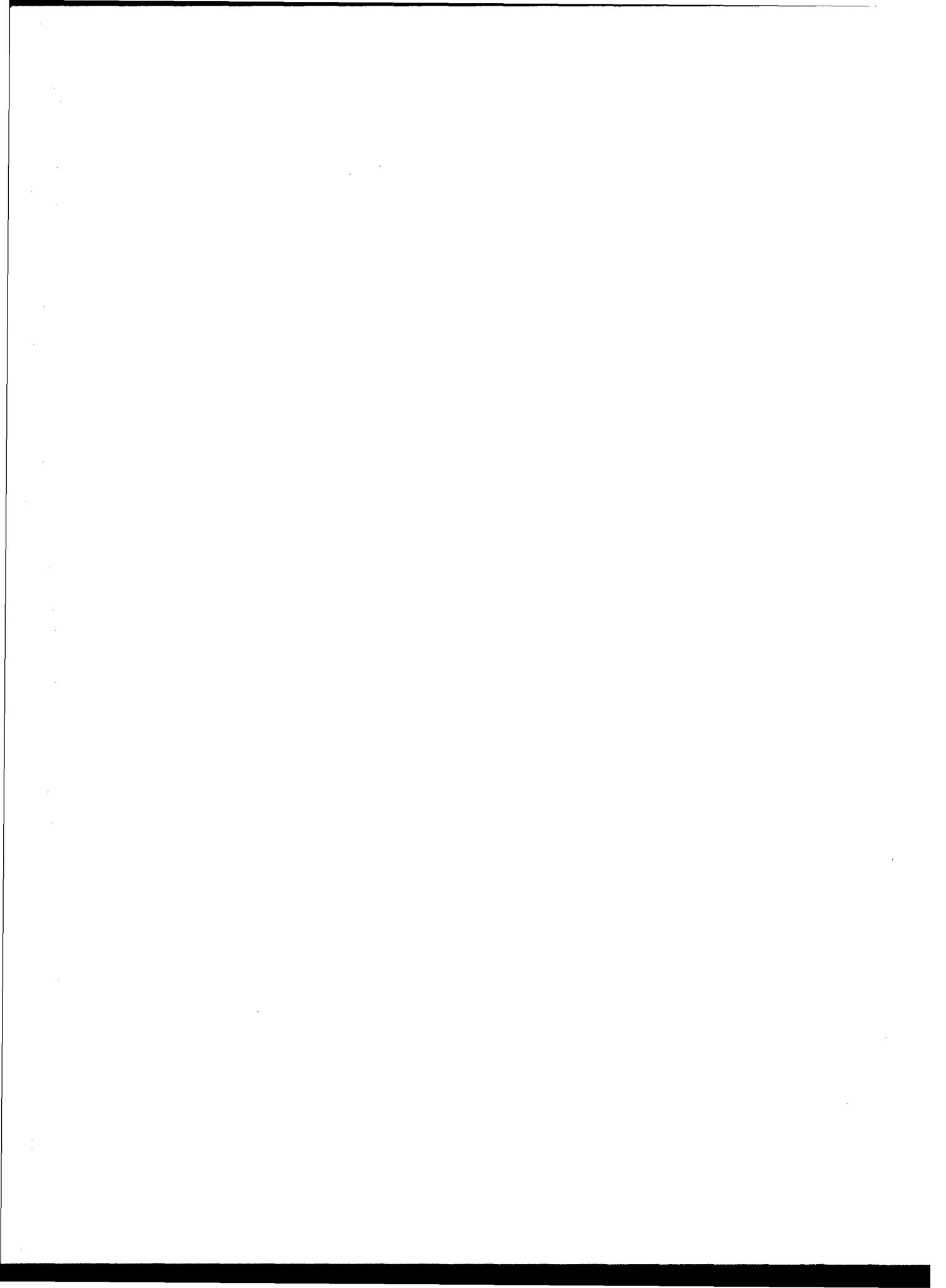
Provision is made in the program for a number of surface boundary conditions. These provisions allow efficient use of the program for analyzing both ground and flight test data and trajectory synthesis.

The computer program has been checked out with both exact solutions and actual ablation test data. The numerical results are in good agreement with the exact solutions and test data. However, the analysis depends upon using good property values, and some effort must be expended in obtaining the best possible thermal properties.

Manned Spacecraft Center  
National Aeronautics and Space Administration  
Houston, Texas, November 1, 1965

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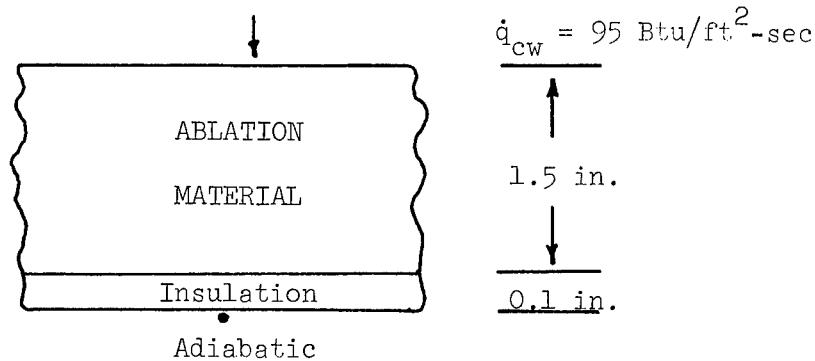
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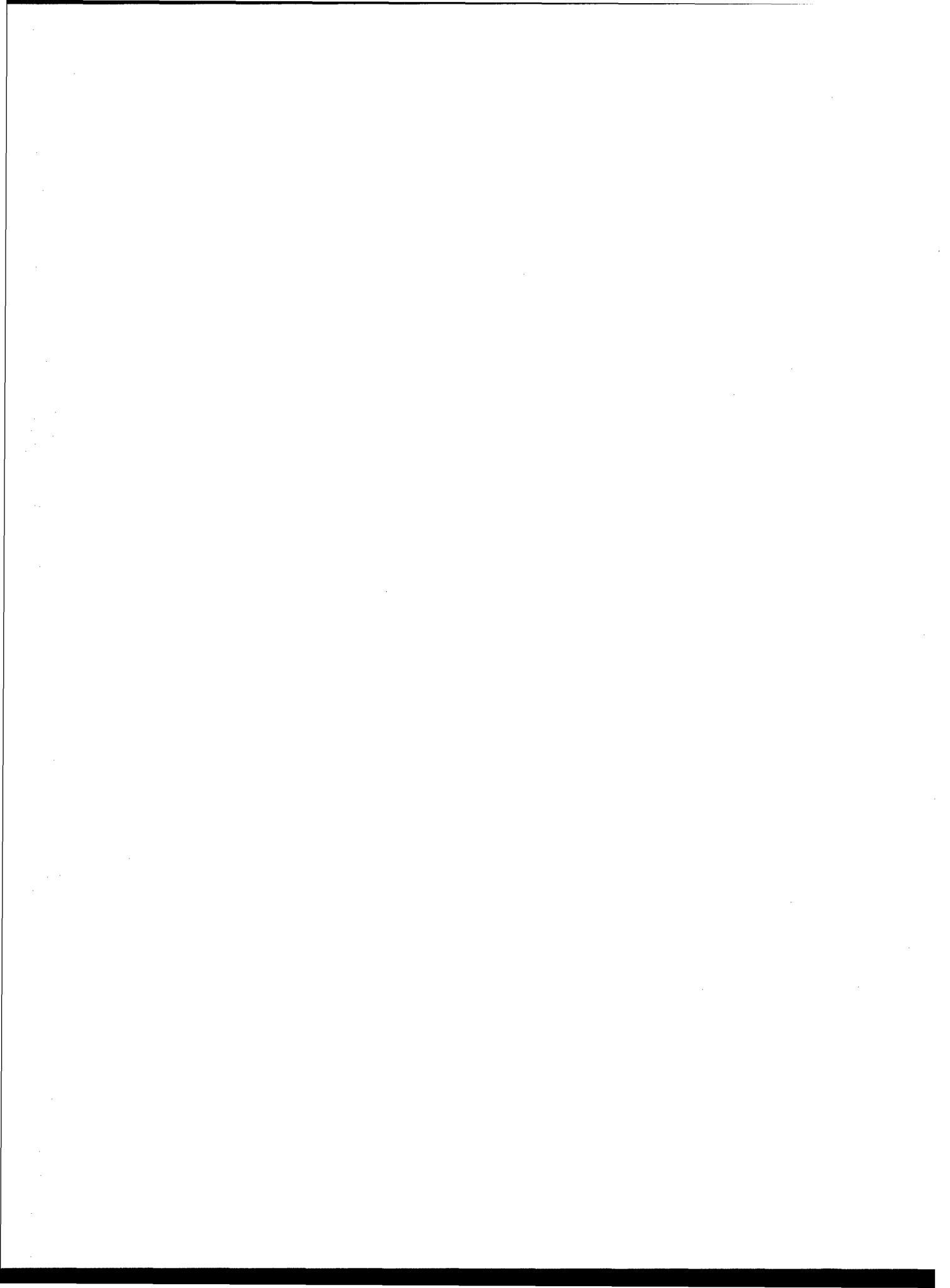
## APPENDIX A

### SAMPLE PROBLEM

The following sample problem is shown to indicate the form of the data input and the program output. A typical charring material subjected to a constant heating rate as experienced in an arc tunnel is presented. The following is a sketch of the model:



The various material properties and dimensions are shown in the program output of Table II. The insulation is assumed to be ablation material for this problem. The problem coding sheet and subsequent data card listing are shown in Table I. The initial temperature of the structure was assumed uniform and equal to 530° R (70° F). Figures 8, 9, and 10 are the output data obtained from the plot routines.



## APPENDIX B

### PROGRAM USAGE INSTRUCTIONS

IBM 7094/40 program F021, standard ablation program, designated STAB II, is designed to evaluate the transient thermal performance of a charring ablation heat protection system. The program considers one ablating material and up to 12 different materials in the supporting backup structure. A maximum of 50 nodes may be considered in the ablation material, and a maximum of 10 nodes per material is allowed for each backup structure material. Air gaps can be considered between successive materials in the backup, thus allowing for both radiative and/or convective heat transfer between materials. The heat loss to the cabin environment from the backup structure can be accomplished by both radiation and/or convection, or an adiabatic backface surface may be prescribed.

Unless otherwise specified, the input problem data are in "floating point" form (E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. It is suggested that each floating point number have a sign, a two-digit exponent, and a decimal point. For example, the number 145.23 can be written as +1.4523 +02, +145.23 +00, or +.14523 +03.

#### Input Nomenclature

The nomenclature used in the problem data input is as follows:

NCASE	number of problems to be run successively
HEAD	any 72 alphabetical and/or numerical characters
TITLE	control card for reading in new input for successive problems
1. blank card - new data will be read in	
2. Six asterisks in columns 1 to 6. Skip to next read statement	
TLIM	time limit of problem, sec
TINT	starting time of problem, sec
NPTT	number of points in time-step table (the minimum value of NPTT is 2)
NPLOT	output plot control
=1	plot routine will be used
=0	plot routine will be ignored

TTABLE	time in time-step table, sec
DELTt	time step to be used for each calculation - starting at time TTABLE, sec
IPRC	variable print frequency in TTABLE table; that is, if DELTT = 1.0 and IPRC = 10, the output will be printed at 10-second intervals
FC $\phi$ NV	factor to correct convective heating rate for various body locations
FRAD	factor to correct radiative heating for various body locations
TABL	temperature at which ablation starts, $^{\circ}$ R
TCHAR	temperature at which ablation stops, $^{\circ}$ R
TREC	surface temperature, $^{\circ}$ R, or time at which char removal is to start, sec
RH $\phi$ V	density of virgin ablation material, lb/ft <sup>3</sup>
RH $\phi$ C	density of mature char material, lb/ft <sup>3</sup>
FBL $\phi$ W	blowing efficiency of ablation gases in reducing convective heating
EMV	emissivity of virgin ablation material
EMC	emissivity of charred ablation material
H300	enthalpy of air at 300 $^{\circ}$ K, 129.06 Btu/lbm
VL	initial thickness of virgin ablation material, in.
HV	heat of degradation of virgin material, Btu/lbm
VPT	test to determine if the reaction zone and char zone thermal properties are irreversible with temperature
=0	properties are irreversible and equal to the value at the maximum individual node temperature (this is the recommended value for VPT)
=1	properties are reversible
FV	view factor for external environment
TV	sink temperature of external environment, $^{\circ}$ R

CHARK	thermal conductivity of material at TCHAR, Btu/ft-hr-°R
CHARC	specific heat of material at TCHAR, Btu/lbm-°R
ABLK	thermal conductivity of material at TABL, Btu/ft-hr-°R
ABLC	specific heat of material at TABL, Btu/lbm-°R
NP	number of node points in ablation material
NKC	number of points in char thermal conductivity - temperature table
NCPC	number of points in char specific heat - temperature table
NKV	number of points in virgin thermal conductivity - temperature table
NCPV	number of points in virgin specific heat - temperature table
NREC	number of points in surface recession - temperature <u>or</u> time table
TKC	temperature values in char thermal conductivity - temperature table, °R
XKC	thermal conductivity values in char thermal conductivity - temperature table, Btu/ft-hr-°R
TCPC	temperature values in char specific heat - temperature table, °R
CPC	specific heat values in char specific heat - temperature table, Btu/lbm-°R
TKV	temperature values in virgin thermal conductivity - temperature table, °R
XKV	thermal conductivity values in virgin thermal conductivity - temperature table, Btu/ft-hr-°R
TCPV	temperature values in virgin specific heat - temperature table, °R
CPV	specific heat values in virgin specific heat temperature table, Btu/lbm-°R
TS	temperature, °R, or time, sec, values in the surface recession table

SR	surface recession values in the surface recession - temperature or time table, in./sec
NTRAPT	number of time points in the trajectory input table
TIME	the array of (NTRAPT) trajectory time values, sec
QC <sub>ON</sub>	the corresponding array of cold wall convective heating rates, Btu/ft <sup>2</sup> -sec
QRAD	the corresponding array of radiative heating rates, Btu/ft <sup>2</sup> -sec
VEL	the corresponding array of flight velocity, ft/sec
NMB	number of materials in backup structure
NPBS	total number of node points in backup structure
BL	total thickness of backup structure, in.
XNPM	number of nodes in <u>each individual</u> material in backup structure
NKPB	number of points in <u>each individual</u> backup structure material thermal conductivity - temperature table
NCPB	number of points in <u>each individual</u> backup structure material specific heat - temperature table
XIDNT	any 72 alphanumeric characters used to describe <u>each individual</u> material in the backup structure
TXK	temperature values in backup material thermal conductivity - temperature table, °R
XK	thermal conductivity values in backup material thermal conductivity - temperature table, Btu/ft-hr-°R
TCP	temperature values in backup material specific heat - temperature tables, °R
CPX	specific heat values in backup material specific heat - temperature tables, Btu/lbm-°R
RH <sub>OBX</sub>	density of individual materials in backup, lb/ft <sup>3</sup>
XBM	thickness of individual materials in backup, in.
EMFB	emissivity of front surface of each material in backup

EMBB	emissivity of back surface of each material in backup
H	film coefficient between adjacent materials in backup, Btu/ft <sup>2</sup> -hr-°R
GAPX	width of gap between adjacent materials in backup, in.
FTEST, BTEST	tests to determine the mode of heat transfer between materials for the front and backface of each material respectively
=0	conduction only between materials
=+1	convective heat transfer only
=-1	radiation only or radiation and convection heat transfer
TENV	temperature of interior cabin environment, °R
HENV	film coefficient to interior cabin environment, Btu/ft <sup>2</sup> -hr-°R
FENV	view factor and emissivity product for radiative heat transfer to cabin interior
QL $\phi$ SS	boundary condition between last node of the backup structure and cabin environment
=0	adiabatic surfaces
=+1	radiation and/or convective loss
TEST2	determines the proper heat shield initial temperature distribution
=0	constant, uniform initial temperature distribution
=-1	arbitrary initial temperature distribution
=+1	linear temperature distribution
TEMPI	temperature to be used when constant temperature distribution option is used, °R
TX $\phi$	initial temperature at front surface of heat shield to be used in computing initial linear temperature gradient, °R
TEMDI	arbitrary temperature distribution values, to be used only if TEST2 is negative, °R

NHP	number of points in enthalpy - temperature curve fit
HX	enthalpy values in enthalpy - temperature table, Btu/lbm
TW	corresponding temperature values in enthalpy - temperature table, °R

### Input Data Card Preparation

The input data are given in the following order. Each number in the following listing refers to a separate record and must begin on a new data card. The input data have been grouped, where possible, into various sections dealing with a particular part of the input, that is, ablation material properties, trajectory data, backup structure, et cetera. This grouping permits the use of a minimum number of input cards for running successive problems. The title card as described in the input nomenclature controls the input for successive problems.

1. The first data card contains the value of NCASE. NCASE is an integer (I5 format) and must end in column 5. This card tells how many problems are to be run and is entered only once at the start of the data deck.

2. Columns 1 to 72 of the second data card contain any title or identification information desired; any alphanumeric character may be used. This card is printed at the top of the first page of the output. This card must be included in all successive problems to be run.

(a) Problem time section

3. TITLE card - if blank, cards 4 and 5 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 6.

4. This record contains, in the following order, TLIM, TINT, NPTT, and NPL $\emptyset$ T. TLIM and TINT are entered as floating-point numbers and must end in columns 12 and 24. NPTT and NPL $\emptyset$ T are integers entered with an I5 format and must end in column 30 and 35.

5. Start entering the values of TTABLE, DELTT, IPRC. TTABLE and DELTT are floating-point numbers and must end in columns 12 and 24. IPRC is entered as integer with an I5 format and must end in column 30. Use as many cards as required to enter NPTT values.

(b) Heating rate factors section

6. TITLE card - if blank, card 7 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 8.

7. Enter the FC<sub>0</sub>NV and FRAD. These numbers are entered as floating-point numbers and must end in columns 12 and 24.

(c) Ablation material section

8. TITLE card - if blank, cards 9 to 18 must be submitted. If six asterisks are punched in columns 1 to 6, skip to record number 19.

9. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 9 to 18 contain input data for the ablation material.

10. Enter TABL, TCHAR, TREC, RH<sub>0</sub>V, RH<sub>0</sub>C, and FBL<sub>0</sub>W. These numbers are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72.

11. Enter EMV, EMC, H<sub>3</sub>OO, VL, HV, and VPT. Use the same format as card 10.

12. Enter FV, TV, CHARK, CHARC, ABLK, and ABLC. Use the same format as card 10.

13. This card contains, in the following order, NP, NKC, NCPC, NKV, NCPV, and NREC. These numbers are fixed-point integers and must end in columns 5, 10, 15, 20, 25, and 30. An I5 format is used to read in these numbers.

14. Start entering the curve of TKC versus XKC, with the values of TKC ending in columns 12, 36, and 60. The corresponding values of XKC must end in columns 24, 48, and 72; for example, three TKC-XKC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter NKC points on the curve.

15. Start entering the curve of TCPC versus CPC with the values of TCPC, ending in columns 12, 36, and 60. The corresponding values of CPC must end in columns 24, 48, and 72; for example, three TCPC-CPC points are contained on one card. The numbers are entered as floating-point numbers. Use as many cards as required to enter the NCPC points on the curve.

16. Start entering the curve of TKV versus XKV with the values of TKV ending in columns 12, 36, and 60. The corresponding values of XKV must end in columns 24, 48, and 72; for example, three TKV-XKV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter the NKV points on the curve.

17. Start entering the curve of TCPV versus CPV with the values of TCPV, ending in columns 12, 36, and 60. The corresponding values of CPV must end in columns 24, 48, and 72; for example, three TCPV-CPV points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPV points on the curve.

18. Start entering the curve of TS versus SR with the values of TX, ending in columns 12, 36, and 60. The corresponding values of SR must end in columns

24, 48, and 72; for example, three TS-SR points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NREC points on the curve.

(d) Trajectory data section

19. TITLE card - if blank, cards 20 to 22 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 23.

20. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 21 and 22 contain trajectory input data.

21. Enter NTRAPT. This number is an integer and must end in column 5. An I5 format is used to read in this number.

22. Start entering the trajectory data in the following order: TIME, QC $\emptyset$ N, QRAD, VEL. These values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48. There are four trajectory data points on one card. Use as many cards as required to enter NTRAPT points in the trajectory.

(e) Backup structure section

23. TITLE card - if blank, cards 24 to 31 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 32.

24. Enter NMB, NPBS, and BL. These three values must end in columns 5, 10, and 24. NMB and NPBS are integers and are read in under an I5 format. BL is a floating-point number.

25. Enter the values of XNPM. XNPM is in floating-point form and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

26. Enter the values of NKPB and NCPB. These numbers are integers and NKPB must end in columns 5, 15, 25, 35, and 45; and the corresponding values of NCPB must end in columns 10, 20, 30, 40, and 50. An I5 format is used to read these values. Five NKPB-NCPB values are contained on one card. Use as many cards as are required to enter NMB points.

27. XIDNT card - any alphanumeric characters in columns 1 to 72. This card contains a description of each backup material.

28. Start entering the curve of TXK versus XK with the values of TXK, ending in columns 12, 36, and 60. The corresponding values of XK must end in columns 24, 48, and 72; for example, three TXK-XK points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NKPB points on the curve.

29. Start entering the curve of TCP versus CPX with the values of TCP, ending in columns 12, 36, and 60. The corresponding values of CPX must end in columns 24, 48, and 72; for example, three TCP-CPX points are contained on one card. The numbers are entered as floating point. Use as many cards as required to enter NCPB points on the curve. Repeat records 27, 28, and 29 until the properties for NMB materials have been entered. The maximum number for NMB is 12.

30. Start entering the following values in order: RH $\phi$ BX, XBM, EMFB, and EMBB. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

31. Start entering the following values in order: H, GAPX, FTEST, and BTEST. These values are entered as floating-point numbers (6E12.8 format) and must end in columns 12, 24, 36, 48, 60, and 72. Use as many cards as required to enter NMB points.

(f) Interior environment section

32. TITLE card - if blank, cards 33 and 34 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record number 35.

33. HEADNG card - any alphanumeric characters in columns 1 to 72. Record 35 contains properties of environment.

34. Enter the following: TENV, HENV, FENV, and QLOSS. The values are entered as floating-point numbers and must end in columns 12, 24, 36, and 48.

(g) Initial temperature section

35. TITLE card - if blank, records 36 and 37 must be submitted; if six asterisks are punched in columns 1 to 6, skip to record 39.

36. HEADNG card - any alphanumeric characters in columns 1 to 72. Records 37 and 38 contain initial temperature distribution input.

37. Enter TEST2, TEMPI, and TX $\phi$ . These values are entered as floating-point numbers and must end in columns 12, 24, and 36.

NOTE: If TEST2 is a negative number, record 38 must be submitted; otherwise, skip to record 39.

38. Enter the arbitrary temperature distribution values, TEMDI. These values are entered as floating points with a 6E12.8 format. Use as many cards as required to enter NP plus NPBS node points.

(h) Enthalpy - temperature section

39. TITLE card - if blank, records 40 and 41 must be submitted; if six asterisks are punched in columns 1 to 6, this is the last data card in the problem input.

40. Enter NHP. This value is an integer and must end in column 5. An I5 format is used to read in this number.

41. Start entering the curve of HX versus TW with the value of HX ending in columns 12, 36, and 60. The corresponding values of TW must end in columns 24, 48, and 72; for example, three HX-TW points are contained on one card. The numbers are entered as floating points. Use as many cards as required to enter NHP points on the curve. Record 41 consists of the last data cards required as input for a problem.

As many successive problems as desired may be run at one time by proper input preparation. STAB II has been designed to save all input information until it is changed by new input data. Therefore, the use of the TITLE control card is very important when running more than one problem and using the input data of previous problems. As shown, each input section starts with a TITLE control card for determining whether new input data are to be used. If any data are changed within a section, then all data cards required for that section must be submitted.

STAB II can also be used for solving one-dimensional transient heat-conduction problems of nonablating materials. The following input parameters must be adhered to:

1. TABL must be greater than the maximum temperature expected during the calculation. Also, TABL > TCHAR > TREC.
2. The ablation material must be considered to be the first material in the structure for calculation purposes.
3. The virgin and char properties must be inputted as described above but can have the same values; that is, XKV = XKC, CPC = CPV, RH $\phi$ V = RH $\phi$ C, et cetera.

The following dimensional statements and program limitations should not be violated when preparing the input described above for ablating and non-ablating structure:

1. All property tables can have a maximum of 20 points (i.e., a temperature and specific heat value constitute one point).
2. The surface recession table can have a maximum of 50 points (TS and SR constitute one point).
3. The trajectory table can have a maximum of 300 points (TIME, QC $\phi$ N, QRAD, and VEL constitute one point).

4. The ablation material can be broken into a maximum of 50 nodes. The backup structure can consist of up to 12 different materials with a maximum of 10 nodes per material.

5. A minimum of three nodes per material (ablation or backup) must be specified.

6. A minimum of two materials must be specified (ablation material and one backup structure material).

7. Pure conduction only is allowed between the ablation material and the first material in the backup.

8. If any data input is changed in the Ablation Material Section on successive problems, the Ablation Material Section data cards plus the Initial Temperature Section data cards must be submitted.

#### Program Output Information

The computed results are available in two forms of output: tabular and plot outputs. The tabular output presents the computed results in block type form for each computation step as controlled by the print count control number. As discussed in the preparation of input data, both the computational time step and print control can be varied throughout the running of a problem. Therefore, excessive printed output is avoided, and there is a considerable savings in actual machine computation time. The plot outputs are printed and plotted only when the entire set of problems to be run are completed.

Tabular output. — The program prints a listing of the data input parameters for identification of the problem and ease in identifying any input mistakes. For stacked problems, the program prints only that input information that is changed from the previous problem. The following calculated problem output is printed:

1. Time, sec
2. Cold wall convective heating rate without blowing,  $\text{Btu}/\text{ft}^2\text{-sec}$
3. Radiative heating rate,  $\text{Btu}/\text{ft}^2\text{-sec}$
4. Velocity, ft/sec
5. Gas ablation rate,  $\text{lbfm}/\text{ft}^2\text{-hr}$
6. Char ablation rate,  $\text{lbfm}/\text{ft}^2\text{-hr}$
7. Total ablation rate,  $\text{lbfm}/\text{ft}^2\text{-hr}$
8. Surface recession depth from original surface, in.

9. Hot wall convective heating rate without blowing,  $\text{Btu}/\text{ft}^2\text{-sec}$
10. Temperature distribution in ablation material,  ${}^\circ\text{R}$
11. Temperature distribution in backup structure,  ${}^\circ\text{R}$

The temperatures printed for the ablation material are for fixed distances from the original surface. These distances are calculated from the initial ablation material thickness and number of nodes in ablation material. For example

let

$$VL = 1.0 \text{ in.}$$

$$NP = 11$$

then

$$\Delta X = \frac{VL}{NP - 1} = 0.1$$

The temperatures will be printed for  $X$  distances of 0, 0.1, 0.2, 0.3, et cetera, from the original surface until the surface has receded beyond these fixed distances at which time the node no longer exists and is dropped from the printout. This is illustrated in the following way: let surface recession = 0.26 inch. The first temperature printed then is the surface temperature of the material, located 0.26 inch from the original material surface. The following printed ablation material temperatures are for  $X$  distances of 0.3, 0.4, 0.5, ..., 1.0 inch.

The format for the temperature distribution printout is E16.5 with six temperatures printed per line.

Plot output. — The plot output gives the following ablative material performance parameters as a function of time:

1. Surface depth, in.
2. Bondline temperature between ablator and backup structure,  ${}^\circ\text{R}$
3. Two selected isotherm depths

These values are also printed in tabular form for ease in checking and replottedting of the results. The plotted curves contain all maximum and minimum values of the parameters.

APPENDIX C

PROGRAM IN FORTRAN STATEMENTS

```

$IBFTC MAIN
C
C      STRUCTURES AND MECHANICS DIVISION
C      THERMO-STRUCTURES BRANCH
C      THERMAL PROTECTION SYSTEMS SECTION
C
C      THIS PROGRAM DETERMINES THE PERFORMANCE OF A CHARRING ABLATOR
C
C      ANALYSIS AND PROGRAM DEVELOPED BY DONALD M. CURRY * ES32
C
C      DIMENSION ESAVE1(3),ESAVF2(3),ESAVE3(3)
C      DIMENSION TITLE(12),HFADNG(12),XIDNT(12,12),TKC(20),XKC(20),
C      1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
C      2RAD(300),VEL(300),XNPM(12),NKPR(12),NCPR(12),TXK(20,12),XK(20,12)
C      3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMFB(12),EMBR(12),HXX(12)
C      4,GAPX(12),FTEST(12),BTTEST(12),TEMDF(200),TX1(200),TX2(200),
C      5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),
C      6IR2(50),TUL(50),IFM(50),TY(200),A(200),R(200),C(200),D(200),
C      7R(50),RH0(50),CP(50),DXR(12),XKR(10,12),CPB(10,12),XMNG(50),
C      8YK(50),AB(10,12),RB(10,12),CR(10,12),DB(10,12),SR(10,12),
C      9RR1(10,12),RB2(10,12),H(12),S(50),NPM(12)
C      DIMENSION TTUL(50),RH0Y1(50),RH0Y2(50),DRH0(50),TCP(20)
C      DIMENSION TIMFP(300),PRFS(300),XC(50),TX2C(50),XV(50),XDV(50)
C      DIMENSION TS(50),SR(50)
C      DIMENSION TTARLE(20),DELLT(20),IPRC(20)
C      DIMENSION ASAVE1(3),ASAVF2(3),ASAVE3(3),BSAVE1(3),BSAVE2(3),
C      1BSAVE3(3),CSAVE1(3),CSAVE2(3),CSAVE3(3),HEAD(12),
C      1DSAVE1(3),DSAVE2(3),DSAVE3(3)
C      DIMENSION XRA(30),YA(30)

C
C      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XRM,FMBR,
C      1FMFR,NKPR,NCPR,TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTTEST,TEMDF,TX1,
C      2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AR,RB,CR,DB,SB,
C      3RR1,RR2,TY,RH0Y1,RH0Y2,XMNG,RHO,CP,YK,XKR,CPB,DXR,DT,XLOST,
C      4TABL,TCHAR,TRFC,RHOV,RHOC,FRBLW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
C      5NP,NMR,NPBS,NPF,TEST2,TFMPI,TX0,TFNV,HENV,FENV,GLOSS,TLM,TINT
C      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,FRR1,ERR2,
C      1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ARLC,XMDC,H

C
3000 FORMAT(12A6)
3001 FORMAT(1X,12A6)
3002 FORMAT(6E12.8)
3003 FORMAT(6I5)
3004 FORMAT(1I5)
3005 FORMAT(2I5)
3007 FORMAT(2I5,1E14.8)
3008 FORMAT(//1X,12A6)
3009 FORMAT(1H1,1X,12A6)
3010 FORMAT(4E12.8)
3011 FORMAT(2E12.8,I6,I5,F13.8,E12.8)
3012 FORMAT(2E12.8,I6)
DATA PRVIOUS/0545454545454/
REWIND 11
STOP=9999.
READ(5,3003)NCASE
LPLOT=0
JCNT=0

```

```

50 NK=1 A0570
I1=2 A0580
I2=2 A0590
I3=2 A0600
I4=2 A0610
I5=2 A0620
I6=2 A0630
I17=2 A0640
INT=1 A0650
XLOST=0.0 A0660
XMT=0.0 A0670
XMDT=0.0 A0680
FRR1=0.0 A0690
FRR2=0.0 A0700
FRR3=0.0 A0710
FRR4=0.0 A0720
ICT=0 A0730
ICONT=0 A0740
XMDC=0.0 A0750
NKP=1 A0760
XLSTV=0.0 A0770
NRS=2 A0780
FRR5=0.0 A0790
TPCT=0 A0800
ICTP=0 A0810
IPLOT=1 A0820
NXA=1 A0830
NXB=1 A0840
NXC=1 A0850
NXD=1 A0860
SAVY3=-100. A0870
SAVY4X=-100. A0880
SX0=0.0 A0890
SDOT=0.0 A0900
A0910
C GFNERAL TITLE OF PROBLEM A0920
100 READ(5,3000) (HEAD(K),K=1,12) A0930
  WRITE(6,3009) (HEAD(K),K=1,12) A0940
  LPLOT=LPLOT+1 A0950
  WRITE (11)(HEAD(I),I=1,12) A0960
  WRITE(6,110) A0970
110 FORMAT(//1X,11HINPUT DATA.//)
  READ(5,3000) (TITLE(L),L=1,12) A0980
  TF(TITLE(1).EQ.PRVIOUS) GO TO 150 A0990
  READ(5,3011) TLIM,TINT,NPTT,NPLOT,DMP,TDMP A1000
  RFAD(5,3012) (TTABLE(I),DFLTT(I),IPRC(I),I=1,NPTT) A1010
  T=TINT A1020
  DTS=DFLTT(1) A1030
  DT=DFLTT(1)/3600.0 A1040
  WRITE(6,120) TLIM,TINT,NPTT A1050
120 FORMAT(1H0,11HTIME LIMIT=,1PE10.4,4X,13HINITIAL TIME=,1PE10.4,4X.5 A1060
  1HNPTT=,I4) A1070
  WRITE(6,122) A1080
122 FORMAT(//8X,4HTIME,10X,9HTIME STEP,6X,13HPRINT CONTROL) A1090
  WRITE(6,124) (TTABLE(I),DFLTT(I),IPRC(I),I=1,NPTT) A1100
124 FORMAT(5X,1PE10.4,6X,1PE10.4,9X,I4) A1110
A1120
A1130

```

```

C LOCATION FACTORS FOR CONVECTIVE AND RADIATIVE HEATING A1140
150 READ(5,3000) (TITLE(L),L=1,12) A1150
    IF(TITLE(1).EQ.PRVOUS) GO TO 200 A1160
    READ(5,3002) FCONV,FRAD A1170
    WRITE(6,155) FCONV,FRAD A1180
155 FORMAT(1H0,6HFCONV=,1PE12.5,4X5HFRAD=,1PF12.5/) A1190
C
C PROPERTIES OF ABLATION MATERIAL A1200
C
200 READ(5,3000) (TITLE(L),L=1,12) A1210
    IF(TITLE(1).EQ.PRVOUS) GO TO 300 A1220
    READ(5,3000) (HEADNG(K),K=1,12) A1230
    RFAD(5,3002) TABL,TCHAR,TREC,PHOV,RHOC,FRILOW,FMV,EMC,H300,VL,HV, A1240
    1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC A1250
    RFA (5,3003) NP,NKC,NCPC,NKV,NCPV,NREC A1260
    READ(5,3002) (TKC(K),XKC(K),K=1,NKC) A1270
    READ(5,3002) (TCP(C(M),CPC(M),M=1,NCPC) A1280
    READ(5,3002) (TKV(L),XKV(L),L=1,NKV) A1290
    RFAD(5,3002) (TCPV(N),CPV(N),N=1,NCPV) A1300
    RFAD(5,3002) (TS(I),SR(I),I=1,NRFC) A1310
    WRITE(6,3008) (HEADNG(K),K=1,12) A1320
    WRITE(6,210) TABL,TCHAR,TREC,PHOV,RHOC,FRILOW,FMV,EMC,H300,VL,HV, A1330
    1VPT,FV,TV,CHARK,CHARC,ABLK,ABLC A1340
210 FORMAT(1H0,5HTABL=,1PF12.5,3X,6HTCHAR=,1PF12.5,3X,5HTREC=,1PE12.5, A1350
    13X,5HRHOV=,1PF12.5,3X,5HRHOC=,1PF12.5,21X/1X,6HFBL0W=,1PE12.5,4X,4 A1360
    2HEMV=,1PE12.5,4X,4HEMC=,1PE12.5,3X,5HH300=,1PE12.5,5X,3HVL=,1PE12. A1370
    35/4X,3HHV=,1PF12.5,4X,4HVPT=,1PF12.5,5X,3HFV=,1PF12.5,5X,3HTV=,1PE A1380
    112.5,2X,6HCHARK=,1PF12.5/1X,6HCHARC=,1PE12.5,3X,5HABLK=,1PE12.5,3X A1390
    2,5HABL0C=,1PE12.5/) A1400
    VLI=VL A1410
    VL=VL/12.0 A1420
    VLV=VL A1430
    WRITE(6,220) NP,NKC,NCPC,NKV,NCPV,NREC A1440
220 FORMAT(2X,3HNP=,1I4,4X,4HNKC=,1I4,4X,5HNCP0=,1I4,4X,4HNKV=,1I4,4X, A1450
    15HNCPV=,1I4,4X,5HNREC=,1T4) A1460
    WRITE(6,221) A1470
221 FORMAT(/32X,15HVIRGIN MATERIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H A1480
    1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT) A1490
    KLLL=MIN0(NKV,NCPV) A1500
    WRITE(6,222) (TKV(L),XKV(L),TCPV(L),CPV(L),L=1,KLLL) A1510
222 FORMAT(2X,1PE12.5,4X,1PE12.5,18X,1PE12.5 ,3X,1PF12.5) A1520
    IF(NKV-NCPV) 223,227,225 A1530
223 KLLLL=KLLL+1 A1540
    WRITE(6,224) (TCPV(L),CPV(L),L=KLLL,NCPV) A1550
224 FORMAT(48X,1PF12.5,3X,1PF12.5) A1560
    GO TO 227 A1570
225 KLLLL=KLLL+1 A1580
    WRITE(6,226) (TKV(L),XKV(L),L=KLLL,NKV) A1590
226 FORMAT(2X,1PE12.5,4X,1PE12.5) A1600
227 WRITE(6,228) A1610
228 FORMAT(/,33X,14HCHAR MATFRIAL/20X,7HTHERMAL,38X,8HSPECIFIC/3X,11H A1620
    1TEMPERATURE,4X,12HCONDUCTIVITY,19X,11HTEMPERATURE,7X,4HHEAT) A1630
    KLLL=MIN0(NKC,NCPC) A1640
    WRITE(6,222) (TKC(L),XKC(L),TCP(C(L),CPC(L),CPC(L),L=1,KLLL) A1650
    IF(NKC-NCPC) 230,235,232 A1660
230 KLLLL=KLLL+1 A1670
    WRITE(6,224) (TCP(C(L),CPC(L),CPC(L),L=KLLL,NCP0) A1680
    GO TO 235 A1690
                                         A1700

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232 K1LLL=K1LL+1 A1710
  WRITE(6,226) (TKC(L),XKC(I),L=K1LL,NKC) A1720
235 WRITE(6,240) A1730
240 FORMAT(//28X,23HSURFACE RECESSSION TABLE//25X,11HTEMPERATURE,8X,11H A1740
   1SP - IN/SFC) A1750
  WRITE(6,245) (TS(I),SR(I),I=1,NRFC) A1760
245 FORMAT(24X,1PF12.5,7X,1PF12.5) A1770
C A1780
C   PROPERTIES OF TRAJECTORY A1790
300 RFAD(5,3000) (TITLE(L),L=1,12) A1800
  IF(TITLE(1),EQ,PRVOUS) GO TO 400 A1810
  RFAD(5,3000) (HEADNG(L),L=1,12) A1820
  RFAD(5,3004) NTRAPT A1830
  RFAD(5,3010) (TIME(K),QCON(K),QRAD(K),VFL(K),K=1,NTRAPT) A1840
  WRITE(6,3008) (HEADNG(L),L=1,12) A1850
  WRITE(6,310) NTRAPT A1860
310 FORMAT(1H0,27H NO. OF TRAJECTORY POINTS =,1I4) A1870
  WRITE(6,320) A1880
320 FORMAT(//8X,4HTIME,8X,12H CONVECTIVE,4X,11H RADIATIVE,7X,8HVELOC A1890
   1ITY)
  WRITE(6,330) (TIME(K),QCON(K),QRAD(K),VFL(K),K=1,NTRAPT) A1900
330 FORMAT(1P4E16.5) A1910
C A1920
C   PROPERTIES OF BACK-UP STRUCTURE A1930
400 RFAD(5,3000) (TITLE(L),L=1,12) A1940
  IF(TITLE(1),EQ,PRVOUS) GO TO 500 A1950
  WRITE(6,410) A1960
410 FORMAT(//10X,31H PROPERTIES OF BACKUP STRUCTURE/) A1970
  RFAD(5,3007) NMP,NPRC,BL A1980
  RFAD(5,3002) (XNPM(K),K=1,NMR) A1990
  RFAD(5,415) (NKPB(I),NCPR(I),I=1,NMB) A2000
415 FORMAT(10J5) A2010
  DO 420 K=1,NMP A2020
    NPM(K)=XNPM(K)+0.000nnnnn A2030
420 CONTINUE A2040
  WRITE(6,425) NMP,NPRC,BL A2050
425 FORMAT(//4X,35HNO. OF MATERIALS IN BACK-UP SHIELD=,1I4/4X,40HTOTAL A2060
  1NUMBER OF NODES IN BACK-UP SHIELD=,1I4/4X,28HTHICKNESS OF BACK-UP A2070
  2SHIELD=,1PE12.5//) A2080
  RL=RL/12.0 A2090
  DO 440 I=1,NMR A2100
    LK=NKPB(I) A2110
    LCP=NCPR(I) A2120
    RFAD(5,3000) ((XIDNT(K,I)),K=1,12) A2130
    RFAD(5,3002) ((TXK(J,I),XK(J,I)),J=1,LK) A2140
    RFAD(5,3002) ((TCP(J,I),CPX(J,I)),J=1,LCP) A2150
    WRITE(6,432) (XIDNT(K,I),K=1,12) A2160
432 FORMAT(//12A6) A2170
  WRITE(6,433) A2180
433 FORMAT(//20X,7HTHFRMAL,38X,8HCPFcIFIC/3X,11HTEMPERATURE,4X,12HCOND A2190
   1ACTIVITY,19X,11HTEMPERATURE,7X,4HHEAT) A2200
  K1LL=MIN0(LK,1CP) A2210
  DO 434 N=1,K1LL A2220
  WRITE(6,222) (TXK(N,I),XK(N,I),TCP(N,I),CPX(N,I)) A2230
434 CONTINUE A2240
  IF(LK-LCP) 435,440,437 A2250
435 K1LLL=K1LL+1 A2260

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DO 436 N=KLLL1,LCP          A2280
  WRITE(6,224) (TCP(N,T),CPX(N,T)) A2290
436 CONTINUE                 A2300
  GO TO 440                 A2310
437 KLLL1=KLLL+1            A2320
  DO 438 N=KLLL1,LK          A2330
    WRITE(6,226) (TXK(N,T),XK(N,I)) A2340
438 CONTINUE                 A2350
440 CONTINUF                A2360
  RFAD(5,3002) (RHORX(L),XRM(L),EMFR(L),EMRR(L),L=1,NMR) A2370
  RFAD(5,3002) (H(J),GAPX(J),FTEST(J),BTTEST(J),J=1,NMR) A2380
  WRITE(6,450)               A2390
450 FORMAT(//55X,10HEMISSIVITY/8X,8HMATERIAL,5X,7HDENSITY,7X,9HTHICKN A2400
  1FSS,7X,5HFRONT,9X,4HBACK,7X,14HNODES/MATERIAL/) A2410
  DO 460 LLJ=1,NMR          A2420
    WRITE(6,455) LLJ,RHORX(LLJ),XPM(LLJ),FMFR(LLJ),FMRB(LLJ),XNPM(LLJ) A2430
455 FORMAT(11X,1I1,8X,1PF10.4,4X,1PF10.4,4X,1PE10.4,4X,1PF10.4,6X,1PF1 A2440
  10.4/)                   A2450
460 CONTINUF                A2460
  WRITE(6,465)               A2470
465 FORMAT(//4X,60HADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP A2480
  1STRUCTURE//11X,8HMATERIAL,5X,16HFILM COEFFICIENT,5X,13HGAP THICKN A2490
  2SS,8X,5HFTEST,13X,5HBTEST) A2500
  DO 480 J=1,NMR          A2510
    WRITE(6,470) J, H(J),GAPX(J),FTEST(J),BTTEST(J) A2520
470 FORMAT(13X,1I3,12X,1PF10.4,9X,1PF10.4,7X,1PE11.4,7X,1PE11.4/) A2530
480 CONTINUE                 A2540
C
C   PROPERTIES OF ENVIRONMENT
500 RFAD(5,3000) (TITLE(L),L=1,12)          A2550
  TF(TITLE(1),FO,PRVIOUS) GO TO 600          A2560
  RFAD(5,3000) (HEADNG(L),L=1,12)          A2570
  RFAD(5,3002) TENV,HENV,FFNV,QLOSS          A2580
  WRITE(6,3008) (HEADNG(L),L=1,12)          A2590
  WRITE(6,520) TENV,HENV,FFNV,QLOSS          A2600
520 FORMAT(/4X,12HTMPERATURE=,1PF12.5,4X,17HFILM COEFFICIENT=,1PF12.5 A2610
  1,4X,12HVIFW FACTOR=,1PE12.5,4X,7HQ LOST=,1PE12.5) A2620
A2630
A2640
C
C   INITIAL TEMPERATURE OF STRUTBUTTON
600 RFAD(5,3000) (TITLE(L),L=1,12)          A2650
  TF(TITLE(1),FO,PRVIOUS) GO TO 700          A2660
  READ(5,3000) (HEADNG(L),L=1,12)          A2670
  NPF=NPF+NPRS                         A2680
  NP=NPF+NPRS                         A2690
  TL=VL+BL                           A2700
  XNP=NP                           A2710
  DX=VL/(XNP-1.0)                      A2720
  DXX=DX                           A2730
  RFAD(5,3002) TEST2,TFMPI,TX0          A2740
  TF(TEST2) 610,620,620                A2750
610 RFAD(5,3002) (TEMPI(K),K=1,NPF)        A2760
  DO 615 K=1,NPF                      A2770
    TX1(K)=TEMPI(K)                  A2780
    TX2(K)=TX1(K)                  A2790
    TUL1(K)=TX1(K)                  A2800
    TUL2(K)=TX1(K)                  A2810
  615 CONTINUE                         A2820
  L=NPF+1                           A2830
A2840

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DO 619 I=1,NMR          A2850
  IN=NPM(I)              A2860
  DO 617 J=1,LN          A2870
    TX2T(J,I)=TFMDI(L)   A2880
    I=L+1                 A2890
617 CONTINUE             A2900
619 CONTINUE             A2910
  GO TO 625              A2920
620 CALL TEMPD            A2930
625 WRITE(6,3008) (HEADNG(L),L=1,12)   A2940
  IF(TEST2) 630,635,640   A2950
630 WRITE(6,632)           A2960
632 FORMAT(4X,52HTEMPERATURE DISTRIBUTION IN HEAT SHIELD IS ARBRITARY/
 1)                      A2970
  WRITE(6,633) (TFMDI(K),K=1,NPF)       A2980
633 FORMAT(1PNE12.5)        A2990
  GO TO 645              A3000
635 WRITE(6,637) TEMP1      A3010
637 FORMAT(//4X,64HTEMPERATURE DISTRIBUTON TN HEAT SHIELD IS UNIFORM
 1AND EQUAL TO ,1PE10.4/)  A3020
  GO TO 645              A3030
640 WRITE(6,641)           A3040
641 FORMAT(4X,54HLINEAR TEMPFRAUTURE DISTRIBUTION ASSUMED TN HEAT SHIEL
 1N/)                   A3050
  WRITE(6,633) (TEMDI(L),L=1,NPF)       A3060
645 IF(DMP) 700,700,646      A3070
646 WRITE(6,647)           A3080
647 FORMAT(//)
648 WRITE(6,649) (TX1(L),TX2(L),L=1,NPF)  A3090
649 FORMAT(2X,1PE12.5,4X,1PE12.5)
  WRITE(6,650)           A3100
650 FORMAT(//)
C
C  FNTHALPY AS A FUNCTION OF TEMPERATURE
700 READ(5,3000) (TITLE(L),L=1,12)       A3110
  TF(TITLE(1),EQ,PRVIOUS) GO TO 725
  READ(5,3004) NHP            A3120
  READ(5,3002) (HX(K),TW(K),K=1,NHP)     A3130
725 DO 728 I=1,NP            A3140
  TR(I)=0                  A3150
  TR1(I)=0                 A3160
  TR2(I)=0                 A3170
  TFM(I)=0                 A3180
  XMDG(T)=0.0               A3190
728 CONTINUE                A3200
  WRITE(6,730)               A3210
730 FORMAT(1H1,12HOUTPUT DATA,//)         A3220
  XC(1)=0.0                 A3230
  DO 740 I=2,NP            A3240
  XC(I)=XC(I-1)+DX         A3250
740 CONTINUE                A3260
  TF(T-TIME(NK)) 765,770,760   A3270
750 NK=NK+1                 A3280
  TF(NK-NTRAPT) 750,750,762   A3290
762 WRITE(6,763) NK           A3300
763 FORMAT(1H0,33H THE VALUE OF NK IS IN ERROR, NK=,1I4)  A3310
  GO TO 905                 A3320
                                         A3330
                                         A3340
                                         A3350
                                         A3360
                                         A3370
                                         A3380
                                         A3390
                                         A3400
                                         A3410

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765	TF(NK-2)	762,766,766	A3420
766	QCONX=QCON(NK-1)+((QCON(NK)-QCON(NK-1))/(TIME(NK)-TIME(NK-1)))		A3430
	1*(T-TIME(NK-1))		A3440
	QCONX=FCONV*QCONX		A3450
	QRADX=QRAD(NK-1)+((QRAD(NK)-QRAD(NK-1))/(TIME(NK)-TIME(NK-1)))		A3460
	1*(T-TIME(NK-1))		A3470
	QRADX=FRAD*QRADX		A3480
	VFLX=VEL(NK-1)+((VEL(NK)-VEL(NK-1))/(TIME(NK)-TIME(NK-1)))		A3490
	1*(T-TIME(NK-1))		A3500
	GO TO 775		A3510
770	QCONX=FCONV*QCON(NK)		A3520
	QRADX=FRAD*QRAD(NK)		A3530
	VFLX=VEL(NK)		A3540
C	COMPUTE HFAT BLOCKAGE AT FRONT SURFACE		A3550
775	TF(I17-1)	778,778,776	A3560
776	TF(I17-NHP)	777,777,778	A3570
777	TF(TX2(INT)-TW(I17))	782,788,780	A3580
778	WRITE(6,779) TX2(INT)		A3590
779	FORMAT(1H0,8I0) THE RANGE OF THE FNTHALPY-TEMPFRATURE CURVF FIT WAS		A3600
	1FXCEEDED AT A TEMPERATURF OF,1E10.4)		A3610
	GO TO 905		A3620
780	I17=I17+1		A3630
	GO TO 776		A3640
782	TF(TX2(INT)-TW(I17-1))	784,788,786	A3650
784	I17=I17-1		A3660
	GO TO 775		A3670
786	HW=HX(I17-1)+((HX(I17)-HX(I17-1))/(TW(I17)-TW(I17-1)))		A3680
	1*(TX2(INT)-Tw(I17-1))		A3690
	GO TO 789		A3700
788	HW=HX(I17)		A3710
789	HTX=H300+((VFI X**2)/50056.5)		A3720
	QBLOCK=(FRLOW*XMDG(INT)*(HTX-HW))/3600.0		A3730
C	COMPUTE HFAT TN DUE TO SURFACE COMBUSTION		A3740
	XMD0=XMDC		A3750
	CALL OXIDAT(XMD0,QOXID)		A3760
C	COMPUTE Q-HOT WALL		A3770
	TF(TDMP.EQ.0.) GO TO 4001		A3780
	TF(T.GE.TDMP) DMP=1.0		A3790
4001	Z=(HTX-Hw)/(HTX-H300)		A3800
	TF(Z-1.0) 790,792,793		A3810
790	TF(Z)	791,791,793	A3820
791	QHW=0.0		A3830
	GO TO 1790		A3840
792	QHW=QCONX		A3850
	GO TO 1790		A3860
793	QHW=Z*QCONX		A3870
1790	ZZZ=(QHW-QBLOCK)/QHW		A3880
	TF(ZZ>0.2) 1798,1798,1794		A3890
1798	QBLOCK=0.8*QHW		A3900
C	NFT HEAT TINTO FRONT SURFACE		A3910
1794	IF(IEM(INT)) 795,795,797		A3920
795	TF(TX2(INT)-TCHAR)	796,796,797	A3930
796	FMX=EMV		A3940
			A3950
			A3960
			A3970
			A3980

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GO TO 798                                A3990
797 IFM(INT)=1                            A4000
  FMX=EMC                                 A4010
798 QIN=QRADX+QHW+QOXID-QRLOCK-(4.8333E-13)*FMX*FV*((TX2(INT)**4)-
  1(TV**4))                                A4020
    IF(DMP) 804,804,800                      A4030
800 WRITE(6,801)                           A4040
801 FORMAT(///)
  WRITE(6,802) QCONX,QRADX,VELX,HTX,HW,Z,QRLOCK,QHW,QOXID,QIN
802 FORMAT(1X,6HQC0NX=,1PF12.5,2X,6HQRADX=,1PF12.5,2X,5HVFLX=,1PF12.5,
  12X,4HHTX=,1PE12.5,2X,3HHW=,1PF12.5/1X,2H7=,1PF12.5,2X,7HQRLOCK=,1P
  2F12.5,2X,4HQHW=,1PE12.5,2X,6HQOXID=,1PE12.5,2X,4HQIN=,1PF12.5/)   A4050
804 QIN=QIN*3600.0                         A4060
A4070
C
C  CHECK FOR FRONT SURFACE RECSSION (CHAR LAYER REMOVAL)
  CALL RECESS(XMDC,XLOST,TRFC,DT,RHOC,TS,SR,TX2(1),NREC,NRS,ERR5,SX0
  1,SDOT,DMP)                             A4080
  TF(ERR5) 8050,8050,905                  A4090
8050 VLV=VLV-XL0ST                        A4100
  XI STV=XLSTV+XL0ST                     A4110
  XI STI=XLSTV*12.0                       A4120
  DXV=VLV/(XNP-1.0)                      A4130
  XV(1)=0.0                               A4140
  DO 1780 I=2,NP                          A4150
  XV(I)=XV(I-1)+DXV                      A4160
1780 CONTINUE                                A4170
  DX=DXV                                  A4180
  TF(ERR4) 806,806,805                   A4190
805 GO TO 905                                A4200
806 CALL COEFF(NPFT,SDOT)                 A4210
  TF(DMP) 8069,8069,8061                  A4220
8061 WRITE(6,8062)                           A4230
8062 FORMAT(/1X,23H COEFFICIENTS FOR SWUFT/)
  DO 8066 I=1,NPFT                         A4240
  WRITE(6,8064) A(I),B(I),C(I),D(I),I
8064 FORMAT(1H0,5HA(I)=,1PF12.5,2X,5HR(I)=,1PF12.5,2X,5HC(I)=,1PE12.5,2
  1X,5HD(I)=,1PE12.5,2X,2HI=,I3)          A4250
8066 CONTINUE                                A4260
8069 TF(ERR2) 807,807,805                  A4270
807 TF(ERR3) 810,810,808                  A4280
808 WRITE(6,809) TKK                      A4290
809 FORMAT(1H0,1AH THE VALUE OF IKK=,1I4)   A4300
  GO TO 905                                A4310
810 CALL SWUFT(A,R,C,D,TY,NPFT,DMP)       A4320
827 DO 828 I=1,NP                          A4330
  TX1(I)=TX2(I)                           A4340
  TX2(I)=TY(I)                           A4350
828 CONTINUE                                A4360
  CALL DON2(XLOST,XV,TX2,NP,XC,TX2C,XDV,KKV,XLSTV,DX)
830 CALL ABLATE                            A4370
  XMDF=XMDG(INT)+XMDC                    A4380
  LT=NPM+1                                A4390
  DO 1815 I=1,NMB                         A4400
  LLT=NPM(1)                                A4410
  TF(I,FQ,1) GO TO 1812                  A4420
  TF(GAPX(I-1),FQ,0,) GO TO 1812        A4430
  KKT=1                                    A4440
A4450
A4460
A4470
A4480
A4490
A4500
A4510
A4520
A4530
A4540
A4550

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GO TO 1813	A4560
1812 KKT=2	A4570
1813 DO 1815 J=KKT,LLT	A4580
TX2T(J,I)=TY(LT)	A4590
LT=LT+1	A4600
1815 CONTINUE	A4610
DO 1819 I=1,NMB	A4620
TF(I,FQ,1) GO TO 1816	A4630
TF(GAPX(I-1),FQ,0,) GO TO 1817	A4640
GO TO 1819	A4650
1816 TX2T(1,1)=TY(NP)	A4660
GO TO 1819	A4670
1817 LX=NPM(I-1)	A4680
TX2T(1,I)=TX2T(LX,I-1)	A4690
1819 CONTINUE	A4700
I M=NPM+1	A4710
DO 833 I=1,NMR	A4720
LZ=NPM(I)	A4730
DO 833 J=1,LZ	A4740
TX2(LM)=TX2T(J,I)	A4750
I.M=LM+1	A4760
833 CONTINUE	A4770
DO 5834 I=2,NPTT	A4780
TF(T-TTABLE(I)) 5835,5835,5834	A4790
5835 DTSE=DFLT(I-1)	A4800
TPRCT=IPRC(I-1)	A4810
DT=DELT(I-1)/3600.0	A4820
GO TO 5A36	A4830
5834 CONTINUE	A4840
DTSE=DFLT(I(NPTT))	A4850
TPRCT=IPRC(NPTT)	A4860
DT=DELT(NPTT)/3600.0	A4870
5836 TCT=ICT+1	A4880
5838 VLTEM=SAVY3	A4890
CALL TSOTHM(XV,TX2,1060.,NP,SAVFIT)	A4900
SAVEIT=SAVEIT+XLSTV	A4910
TF(SAVY3.LT.SAVFIT)SAVY3=SAVFIT	A4920
IF(VLTEM.FQ.SAVY3)GO TO A39	A4930
SAVX=T	A4940
SAVY1=XLSTI	A4950
SAVY2=TX2(NP)	A4960
CALL TSOTHM(XV,TX2,1460.,NP,SAVY4)	A4970
839 RI TFME=SAVY4X	A4980
CALL TSOTHM(XV,TX2,1460.,NP,WFKFP)	A4990
WFKFP=WEKEEP+XLSTV	A5000
TF(SAVY4X.LT.WEKEFP)SAVY4X=WEKEFP	A5010
IF(BLTEM.FQ.SAVY4X)GO TO A38	A5020
SAVEXX=T	A5030
SAVY1X=XLSTI	A5040
SAVY2X=TX2(NP)	A5050
CALL TSOTHM(XV,TX2,1060.,NP,SAVY3X)	A5060
838 CONTINUE	A5070
IF(IPRCT-TCT) 835,835,840	A5080
835 WRITE(6,837) T,QCONX,QRANX,VFLX,XMDG(INT),XMDC,XMDT,XLSTI,QHW	A5090
837 FORMAT(1H0,5HTIME=,	A5100
1PF12.5,2X,12HQCONVFCTIVE=,1PF12.5,2X,11HQRADTAT	A5110
1TVE=,1PE12.5,2X,9HVFLOCITY=,1PE12.5/1X,18HGAS APLATION RATE=,1PF12	A5120

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2.5,2X,19HCHAR ABLATION RATE=,1PF12.5,2X,20HTOTAL ABLATION RATE=,1P      A5130
3F12.5/1X,16HRCSESSION DFPTH=,1PF12.5,2X,10HQHOT WALL=,1PE12.5)      A5140
840 T=T+DTS                                         A5150
841 IF(NPLOT.NE.1) GO TO 842                         A5160
    CALL SAVE(ASAVE1,ASAVF2,ASAVF3,USEA,NXA,XLSTI,DTS,TLIM,T,VALUFA)   A5170
    CALL SAVE(BSAVE1,RSAVF2,BSAVF3,USFB,NXB,TX2(NP),DTS,TLIM,T,VALUFR) A5180
    CALL ISOOTHM(XV,TX2,1060.,NP,Y3)                                A5190
    CALL SAVE(CSAVE1,CSAVF2,CSAVF3,USFC,NXC,Y3,DTS,TLIM,T,VALUEC)   A5200
    CALL ISOOTHM(XV,TX2,1460.,NP,Y4)                                A5210
    CALL SAVE(DSAVE1,DSAVF2,DSAVF3,USED,NXD,Y4,DTS,TLIM,T,VALUED)   A5220
    TF(USFA,NF.0.0)GO TO 9842                                     A5230
    TF(USFB,NF.0.0)GO TO 9842                                     A5240
    TF(USFC,NF.0.0)GO TO 9842                                     A5250
    TF(USFD,NF.0.0)GO TO 9842                                     A5260
    GO TO 9843                                              A5270
9842 XPL0T=T-DTS                                     A5280
    YPL0T1=VALUEA                                     A5290
    IF(USFA,NF.0.0)YPL0T1=USFA
    YPL0T2=VALUER                                     A5300
    IF(USFB,NF.0.0)YPL0T2=USFR
    YPL0T3=VALUEC                                     A5310
    IF(USFC,NF.0.0)YPL0T3=USEC
    YPL0T4=VALUED                                     A5320
    IF(USFD,NF.0.0)YPL0T4=USFD
    WRITE (11)XPL0T,YPL0T1,YPL0T2,YPL0T3,YPL0T4
9843 IF(ICTP,NF.0) GO TO 842                         A5330
    TCTP=1
    XPL0T=T
    YPL0T1=XLSTI                                     A5340
    YPL0T2=TX2(NP)
    CALL ISOOTHM(XV,TX2,1060.,NP,YPL0T3)           A5350
    CALL ISOOTHM(XV,TX2,1460.,NP,YPL0T4)           A5360
    WRITE (11)XPL0T,YPL0T1,YPL0T2,YPL0T3,YPL0T4
842 IF(IPRCT-TCT) 845,845,900
845 WRITE(6,850) T
    IPCT=IPCT+1
    IF(IPCT.EQ.2)IPCT=0
    IF(IPCT.EQ.0)ICTP=0
850 FORMAT(1H0,72HTEMPERATURE DISTRIRUTION IN HEAT SHIELD AT THE END 0 A5370
    1F THE TIME STEP, T= ,1PE12.5,1X,7HSFCONDS//) A5380
    WRITE(6,860)
860 FORMAT(4X,49HTEMPFRATURE DISTRIBUTION IN THE ABLATING MATERIAL//) A5390
    KKV=KKV+1
    WRITE(6,862) (TX2C(I),I=1,KKV)                A5400
862 FORMAT(6X,1PF12.5,1P5F16.5)                      A5410
    TJ=NP+1
    WRITE(6,864)
864 FORMAT(//4X,40HTEMPERATURF DISTRIBUTION IN THE BACK-UP STRUCTURE// A5420
    1)
    WRITE(6,862) (TX2(I),I=IJ,NPF)                 A5430
    WRITE(6,865)
865 FORMAT(//)
    TCT=0
900 CONTINUE
    IF(T-TLIM) 750,750,905
905 IF(NPLOT.NE.1) GO TO 909
    XAVY3=SAVY3-SAVY1/12.                           A5440
                                                                A5450
                                                                A5460
                                                                A5470
                                                                A5480
                                                                A5490
                                                                A5500
                                                                A5510
                                                                A5520
                                                                A5530
                                                                A5540
                                                                A5550
                                                                A5560
                                                                A5570
                                                                A5580
                                                                A5590
                                                                A5600
                                                                A5610
                                                                A5620
                                                                A5630
                                                                A5640
                                                                A5650
                                                                A5660
                                                                A5670
                                                                A5680
                                                                A5690

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XAVY4X=SAVY4X-SAVY1X/12. A5700
TF(SAVX,EQ,XPLOT)GO TO 9005 A5710
WRITE(11)SAVX,SAVY1,SAVY2,XAVY3,SAVY4 A5720
9005 TF(SAVEXX,EQ,XPLOT)GO TO 9006 A5730
SAV4I=SAVY4X*12. A5760
9006 SAV3I=SAVY3*12. A5750
WRITE(11)SAVEXX,SAVY1X,SAVY2X,SAVY3X,XAVY4X A5740
WRITE(6,929)SAV3I,SAV4I A5770
929 FORMAT(1H0,23HMAXIMUM 1060 ISOTHFRM =E16.8,2X23HMAXIMUM 1460 ISOTH A5780
1FRM =E16.8)
WRITE(11)STOP,STOP,STOP,STOP,STOP A5790
909 TF(LPLOT.NE.NCASE)GO TO 911 A5800
DATA FND/6H FND /
WRITE(11)FND,FND,END,FND,FND,END,FND,FND,FND,END,FND A5820
QUIT=A888. A5840
WRITE(11)QUIT,QUIT,QUIT,QUIT,QUIT A5850
FND FILE 11 A5860
REWIND 11 A5870
911 TF(TEST2) 910,930,930 A5880
910 DO 920 JJK=1,NPF A5890
TX1(JJK)=TEM01(JJK) A5900
TX2(JJK)=TX1(JJK) A5910
TUL1(K)=TX1(K) A5920
TUL2(K)=TX1(K) A5930
920 CONTINUE A5940
TL=NPF+1 A5950
DO 926 I=1,NMR A5960
TLN=NPM(I) A5970
DO 924 J=1,ILN A5980
TX2T(J,I)=TEM01(IL) A5990
TL=IL+1 A6000
924 CONTINUE A6010
926 CONTINUE A6020
GO TO 940 A6030
930 CALL TEMPO A6040
940 T=TINT A6050
DX=DXX A6060
NTS=DFLTT(1) A6070
DT=DELT(1)/3600.0 A6080
VI.V=VL A6090
GO TO 50 A6100
END A6110

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$IBFTC COEF          B0000
C THIS SUBROUTINE DETERMINES THE COEFFICIENTS OF THE MATRIX      B0010
SUBROUTINE COEFF(NPFT,SDOT)                                     B0020
C
DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20),      B0030
1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),      B0040
2QRAD(300),VEL(300),XNPM(12),NKPB(12),NCPB(12),TXK(20,12),XK(20,12)      B0050
3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBB(12),HXX(12)      B0060
4,GAPX(12),FTEST(12),BTTEST(12),TEMDI(200),TX1(200),TX2(200),      B0070
5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50),      B0080
6IR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),      B0090
7R(50),RHO(50),CP(50),DXB(12),XKB(10,12),CPB(10,12),XMDG(50),      B0100
8YK(50),AB(10,12),BB(10,12),CB(10,12),DB(10,12),SB(10,12),      B0110
9RB1(10,12),RB2(10,12),H(12),S(50),NPM(12)                      B0120
DIMENSION TTUL(50),RH0Y1(50),RH0Y2(50),DRH0(50),TCP(20)           B0130
C
COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XBM,EMBB,      B0140
1EMFB,NKPB,NCPB, TXK,XK,TCP,CPX,NPM,GAPX,FTEST,BTEST,TEMDI,TX1,      B0150
2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CB,DB,SB,      B0160
3RB1,RB2,TY,RH0Y1,RH0Y2,XMDG,RHO,CP,YK,XKB,CPB,DXB,DT,XLOST,      B0170
4TABL,TCHAR,TREC,RHOV,RHOC,FBLW,EMV,EMC,H300,NKC,NCPC,NKV,NCPV,      B0180
5NP,NMB,NPBS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT      B0190
COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,ERR1,ERR2,      B0200
1ERR3,ERR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMDC,H                      B0210
C
CALL PROP             B0220
YNP=NP                B0230
S(INT)=(RHO(INT)*DX*CP(INT))/(2.0*DT)                           B0240
R(INT)=(1.0)/((DX/2.0)*((1.0/YK(INT))+(1.0/YK(INT+1))))       B0250
A(INT)=0.0              B0260
B(INT)=(-(XMDG(INT)+XMDC)*CP(INT)+S(INT)+R(INT)-RHO(INT)*CP(INT)) B0270
1*(SDOT/(2.0*(YNP-1.0))))                                     B0280
C(INT)=XMDG(INT+1)*CP(INT+1)+R(INT)+RHO(INT+1)*CP(INT+1)*SDOT   B0290
1*((YNP-1.5)/(YNP-1.0))                                       B0300
D(INT)=(-(QIN+S(INT)*TX2(INT))) +(XMDG(INT)-XMDG(INT+1))*HV     B0310
NPP=NPP-1               B0320
JNT=INT+1               B0330
DO 10 I=JNT,NPP        B0340
XI=I                  B0350
S(I)=(RHO(I)*DX*CP(I))/DT                                      B0360
R(I)=(1.0)/((DX/(2.0*YK(I)))+(DX/(2.0*YK(I+1))))            B0370
A(I)=R(I-1)             B0380
B(I)=(-(XMDG(I)*CP(I)+R(I-1)+R(I)+S(I)+ RHO(I)*CP(I)*SDOT*((YNP-XI-0.5)/(YNP-1.0)))) B0390
C(I)=XMDG(I+1)*CP(I+1)+R(I)+RHO(I+1)*CP(I+1)*SDOT*((YNP-XI-0.5)/(YNP-1.0)) B0400
1/(YNP-1.0))                                         B0410
D(I)=(-(S(I)*TX2(I))) +(XMDG(I)-XMDG(I+1))*HV                 B0420
10 CONTINUE             B0430
R(NP)=(1.0)/((DXB(1) / (2.0*XKB(1,1)))+(DXB(1) / (2.0*XKB(2,1)))) B0440
S(NP)=(RHO(NP)*DX*CP(NP)+RHOBX(1)* CPB(1,1)*DXB(1))/(2.0*DT)      B0450
A(NP)=R(NP-1)             B0460
B(NP)=(-(XMDG(NP)*CP(NP)+R(NP-1)+R(NP)+S(NP)))      B0470
C(NP)=R(NP)               B0480
D(NP)=(-S(NP)*TX2(NP)) +XMDG(NP)*HV                         B0490
DO 200 I=1,NMB           B0500
IF(I-1) 20,20,30          B0510
20 AB(1,I)=A(NP)          B0520
BB(1,I)=B(NP)             B0530
CB(1,I)=C(NP)             B0540
DB(1,I)=D(NP)             B0550

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      GO TO 65                                B0600
30 L=NPM(I-1)                                B0610
      IF(FTEST(I)) 45,40,45                  B0620
40 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I)+RHOBX(I-1)*CPB(L,I-1)*DXB(I-1))/ B0630
   1(2.0*DT)                                B0640
      RB1(1,I)=(1.0)/((DXB(I-1)/(2.0*XKB(L,I-1)))+(DXB(I-1)/(2.0*XKB(L-1 B0650
   1,I-1))))                                B0660
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I)))) B0670
      AB(1,I)=RB1(1,I)                        B0680
      BB(1,I)=(-(RB1(1,I)+RB2(1,I)+SB(1,I))) B0690
      CB(1,I)=RB2(1,I)                        B0700
      DB(1,I)=(-(SB(1,I)*TX2T(1,I)))        B0710
      GO TO 65                                B0720
45 IF(FTEST(I)) 50,40,55                  B0730
50 G=(1.73E-09)/(1.0/EMBB(I-1)+1.0/EMFB(I)-1.0) B0740
      GO TO 60                                B0750
55 G=0.0                                    B0760
60 SB(1,I)=(RHOBX(I)*CPB(1,I)*DXB(I))/(2.0*DT) B0770
      RB2(1,I)=(1.0)/((DXB(I)/(2.0*XKB(1,I)))+(DXB(I)/(2.0*XKB(2,I)))) B0780
      AB(1,I)=H(I-1)+4.0*G*(TX2T(L,I-1)**3) B0790
      BB(1,I)=(-(H(I-1)+4.0*G*(TX2T(1,I)**3)+RB2(1,I)+SB(1,I))) B0800
      CB(1,I)=RB2(1,I)                        B0810
      DB(1,I)=3.0*G*((TX2T(L,I-1)**4)-(TX2T(1,I)**4))-SB(1,I)*TX2T(1,I) B0820
65 LF=NPM(I)-1                            B0830
      DO 100 J=2,LF                          B0840
      SB(J,I)=(RHOBX(I)*CPB(J,I)*DXB(I))/DT B0850
      RB1(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J-1,I)))+(DXB(I)/(2.0*XKB(J,I)))) B0860
      RB2(J,I)=(1.0)/((DXB(I)/(2.0*XKB(J+1,I)))+(DXB(I)/(2.0*XKB(J,I)))) B0870
      AB(J,I)=RB1(J,I)                      B0880
      BB(J,I)=(-(RB1(J,I)+RB2(J,I)+SB(J,I))) B0890
      CB(J,I)=RB2(J,I)                      B0900
      DB(J,I)=(-(SB(J,I)*TX2T(J,I)))       B0910
100 CONTINUE                                B0920
      IF(I-NMB) 110,250,250                B0930
110 LNF=NPM(I)                            B0940
      IF(BTEST(I)) 120,115,120            B0950
115 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I)+RHOBX(I+1)*CPB(1,I+1)*DXB(I+ B0960
   111))/(2.0*DT)                          B0970
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF B0980
   1,I))))                                B0990
      RB2(LNF,I)=(1.0)/((DXB(I+1)/(2.0*XKB(1,I+1)))+(DXB(I+1)/ B1000
   1(2.0*XKB(2,I+1))))                    B1010
      AB(LNF,I)=RB1(LNF,I)                 B1020
      BB(LNF,I)=(-(RB1(LNF,I)+RB2(LNF,I)+SB(LNF,I))) B1030
      CB(LNF,I)=RB2(LNF,I)                 B1040
      DB(LNF,I)=(-(SB(LNF,I)*TX2T(LNF,I))) B1050
      GO TO 200                                B1060
120 IF(BTEST(I)) 125,115,127            B1070
125 G=(1.73E-09)/(1.0/EMBB(I)+1.0/EMFB(I+1)-1.0) B1080
      GO TO 130                                B1090
127 G=0.0                                    B1100
130 SB(LNF,I)=(RHOBX(I)*CPB(LNF,I)*DXB(I))/(2.0*DT) B1110
      RB1(LNF,I)=(1.0)/((DXB(I)/(2.0*XKB(LNF-1,I)))+(DXB(I)/(2.0*XKB(LNF B1120
   1,I))))                                B1130
      AB(LNF,I)=RB1(LNF,I)                 B1140
      BB(LNF,I)=(-(RB1(LNF,I)+H(I)+SB(LNF,I)+4.0*G*(TX2T(LNF,I)**3))) B1150
      CB(LNF,I)=H(I)+4.0*G*(TX2T(1,I+1)**3) B1160
      DB(LNF,I)=3.0*G*((TX2T(1,I+1)**4)-(TX2T(LNF,I)**4))-SB(LNF,I)*TX2T B1170
   1(LNF,I)                                B1180
200 CONTINUE                                B1190

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250 MN=NPM(NMB) B1200
    IF(QLLOSS) 270,260,270 B1210
260 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT) B1220
    RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*XK
    1B(MN,NMB)))) B1230
    AB(MN,NMB)=RB1(MN,NMB) B1240
    BB(MN,NMB)=(-(RB1(MN,NMB)+SB(MN,NMB))) B1250
    CB(MN,NMB)=0.0 B1260
    DB(MN,NMB)=(-(SB(MN,NMB)*TX2T(MN,NMB))) B1270
    GO TO 280 B1280
270 SB(MN,NMB)=(RHOBX(NMB)*CPB(MN,NMB)*DXB(NMB))/(2.0*DT) B1290
    RB1(MN,NMB)=(1.0)/((DXB(NMB)/(2.0*XKB(MN-1,NMB)))+(DXB(NMB)/(2.0*X
    1KB(MN,NMB)))) B1300
    AB(MN,NMB)=RB1(MN,NMB) B1310
    BB(MN,NMB)=(-(RB1(MN,NMB)+HENV+(1.73E-09)*FENV*4.0*(TX2T(MN,NMB)**
    13)+SB(MN,NMB))) B1320
    CB(MN,NMB)=0.0 B1330
    DB(MN,NMB)=(-(HENV*TENV+FENV*(1.73E-09)*((TENV**4)+3.0*(TX2T(MN,NM
    1B)**4))+SB(MN,NMB)*TX2T(MN,NMB))) B1340
1350
280 L=NP+1 B1350
    DO 300 I=1,NMB B1360
    K=NPM(I) B1370
    IF(I.EQ.1) GO TO 282 B1380
    IF(GAPX(I-1).EQ.0.) GO TO 282 B1390
    KT=1 B1400
    GO TO 285 B1410
282 KT=2 B1420
285 DO 290 J=KT,K B1430
    A(L)=AB(J,I) B1440
    B(L)=BB(J,I) B1450
    C(L)=CB(J,I) B1460
    D(L)=DB(J,I) B1470
    IF(DMP) 289,289,286 B1480
286 WRITE(6,287) AB(J,I),BB(J,I),CB(J,I),DB(J,I),J,I,A(L),B(L),C(L),D(
    1L),L B1490
287 FORMAT(1H0,8HAB(J,I)=,1PE12.5,2X,8HBB(J,I)=,1PE12.5,2X,8HCB(J,I)=,
    1PE12.5,2X,8HDB(J,I)=,1PE12.5,2X,2HJ=,I3,2X,2HI=,I3/1X,5HA(L)=,1PE
    212.5,2X,5HB(L)=,1PE12.5,2X,5HC(L)=,1PE12.5,2X,5HD(L)=,1PE12.5,2X,2
    3HL=,I3) B1500
289 L=L+1 B1510
290 CONTINUE B1520
300 CONTINUE B1530
    NPFT=L-1 B1540
    RETURN B1550
    END B1560

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$IBFTC PRP
C      THIS SUBROUTINE DETERMINES THE PHYSICAL PROPERTIES OF THE
C      HEAT SHIELD STRUCTURE
C      SUBROUTINE PROP
C
C      DIMENSION TITLE(12),HFADNG(12),XIDNT(12,12),TKC(20),XKC(20),
C      1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
C      2RAD(300),VEL(300),XNPM(12),NKPR(12),NCPR(12),TXK(20,12),XK(20,12)
C      3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMBR(12),EMBR(12),HXX(12)
C      4,GAPX(12),FTFST(12),ATEST(12),TEMDF(200),TX1(200),TX2(200),
C      5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),TR1(50),
C      6TR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
C      7R(50),RHO(50),CP(50),DXP(12),XKB(10,12),CPB(10,12),XMNG(50),
C      8YK(50),AB(10,12),BB(10,12),CR(10,12),DB(10,12),SR(10,12),
C      9RR1(10,12),RR2(10,12),H(12),S(50),NPM(12)
C      DTIMENSION TTUL(50),RH0Y1(50),RH0Y2(50),DRHO(50),TCP(20)
C
C      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XPM,FMBR,
C      1FMBR,NKPB,NCPR,TXK,XK,TCP,CPX,NPM,GAPX,FTFST,ATEST,TEMDF,TX1,
C      2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AR,RB,CR,DR,SR,
C      3RP1,RR2,TY,RH0Y1,RH0Y2,XMNG,RHO,CP,YK,XKB,CPB,DXR,DT,XLOST,
C      4TABL,TCHAR,TRFC,RHOV,RHOC,FBLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
C      5NP,NMR,NPRS,NPF,TFST2,TEMPI,TX0,TENV,HENV,FENV,GLOSS,TLIM,TINT
C      COMMON I1,I2,I3,I4,I5,I6,QIN,TNT,DX,XMT,TL,VL,BL,DMP,FRR1,ERR2,
C      1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ARLC,XMDC,H
C
C      KINT=TNT
C      DO 170 I=KINT,NP
C      10 IF(IR(I)) 12,12,100
C      12 TUL(I)=AMAX1(TX1(I),TX2(I))
C      13 IF(TUL(I).LE.TARL) GO TO 20
C      14 IR(I)=1
C      15 GO TO 100
C      20 IF(I1-1) 25,2 ,21
C      21 IF(I1-NKV) 22,22,25
C      22 IF(TX2(I)-TKV(I1)) 35,55,30
C      25 WRITE(6,26) TX2(I)
C      26 FORMAT(1H0,87H THE RANGE OF ONE OF THE ABLATION PROPERTY CURVE FIT
C      1S WAS EXCEEDED AT A TEMPERATURE OF ,1PE12.5)
C      27 FRR2=1.0
C      28 GO TO 355
C      30 I1=I1+1
C      31 GO TO 21
C      35 YK(I)=XKV(I1-1)+((XKV(I1)-XKV(I1-1))/(TKV(I1)-TKV(I1-1)))
C      36 1*(TX2(I)-TKV(I1-1))
C      37 GO TO 60
C      55 YK(I)=XKV(I1)
C      60 IF(I2-1) 25,25,61
C      61 IF(I2-NCPV) 62,62,25
C      62 IF(TX2(I)-TCPV(I2)) 70,85,65
C      65 I2=I2+1
C      66 GO TO 61
C      70 IF(TX2(I)-TCPV(I2-1)) 75,85,80
C      75 I2=I2-1

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```

      GO TO 60
80 CP(I)=CPV(I2-1)+((CPV(I2)-CPV(I2-1))/(TCPV(I2)-TCPV(I2-1)))
1*(TX2(I)-TCPV(I2-1))
      GO TO 90
85 CP(I)=CPV(I2)
90 RHO(I)=RHOV
      GO TO 170
100 TUL(I)=AMAX1(TUL(I),TX2(I))
      TF(TUL(I)-TCHAR) 110,110,115
110 RHO(I)=RHOV+(RHOV-RHOC)*(TUL(I)-TABL)/(TABL-TCHAR)
      YK(I)=CHARK+(ABLK-CHARK)*((RHO(I)-RHOC)/(RHOV-RHOC))
      CP(I)=CHARC+(ABLC-CHARC)*((RHO(I)-RHOC)/(RHOV-RHOC))
      GO TO 170
115 TF(VPT) 116,116,117
116 TTUL(I)=TUL(I)
      GO TO 120
117 TTUL(I)=TX2(I)
120 TF(I3-1) 25,25,121
121 TF(I3-NKC) 122,122,25
122 TF(TTUL(I)-TKC(I3)) 124,135,123
123 I3=I3+1
      GO TO 121
124 TF(TTUL(I)-TKC(I3-1)) 125,135,130
125 I3=I3-1
      GO TO 120
130 YK(I)=XKC(I3-1)+((XKC(I3)-XKC(I3-1))/(TKC(I3)-TKC(I3-1)))
1*(TTUL(I)-TKC(I3-1))
      GO TO 140
135 YK(I)=XKC(I3)
140 TF(I4-1) 25,25,141
141 TF(I4-NCPC) 142,142,25
142 TF(TTUL(I)-TCPC(I4)) 150,165,145
145 I4=I4+1
      GO TO 141
150 TF(TTUL(I)-TCPC(I4-1)) 155,165,160
155 I4=I4-1
      GO TO 140
160 CP(I)=CPC(I4-1)+((CPC(I4)-CPC(I4-1))/(TCPC(I4)-TCPC(I4-1)))
1*(TTUL(I)-TCPC(I4-1))
      GO TO 166
165 CP(I)=CPC(I4)
166 RHO(I)=RHOC
170 CONTINUE
C
C      DETERMINATION OF PROPER BACK-UP SHIELD MATERIAL PROPERTY
C
      DO 300 I=1,NMR
      NXB(I)=XBM(I)/((XNPM(I)-1.0)*12.0)
      LKP=NKPB(I)
      LCP=NCPB(I)
      NN=NPM(I)
      DO 280 J=1,NN
200 TF(I5-1) 203,203,201
201 TF(I5-LKP) 202,202,203
202 TF(TX2T(J,I)-TXK(I5,I)) 206,220,205
203 WRITE(6,204) I,TX2T(J,I)
204 FORMAT(1H0,32H THE RANGE OF ONE OF THE NUMBER ,I2,71H BACKUP STRUCT
      C0570
      C0580
      C0590
      C0600
      C0610
      C0620
      C0630
      C0640
      C0650
      C0660
      C0670
      C0680
      C0690
      C0700
      C0710
      C0720
      C0730
      C0740
      C0750
      C0760
      C0770
      C0780
      C0790
      C0800
      C0810
      C0820
      C0830
      C0840
      C0850
      C0860
      C0870
      C0880
      C0890
      C0900
      C0910
      C0920
      C0930
      C0940
      C0950
      C0960
      C0970
      C0980
      C0990
      C1000
      C1010
      C1020
      C1030
      C1040
      C1050
      C1060
      C1070
      C1080
      C1090
      C1100
      C1110
      C1120
      C1130

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1TURE PROPERTY CURVE FITS WAS EXCFFEDD AT A TEMPFRAUTRE OF ,1PF12.5      C1140
2)                                              C1150
    FRR2=1.0                                     C1160
    GO TO 355                                     C1170
205  T5=I5+1                                     C1180
    GO TO 201                                     C1190
206  TF(TX2T(J,I)-TXK(I5-1,I)) 210,220,215      C1200
210  T5=I5-1                                     C1210
    GO TO 200                                     C1220
215  XKB(J,I)=XK(I5-1,I)+((XK(T5,I)-XK(I5-1,I))/(TXK(T5,I)-TXK(I5-1,I))  C1230
    1)*(TX2T(J,I)-TXK(I5-1,I))                  C1240
    GO TO 230                                     C1250
220  XKB(J,I)=XK(I5,I)                           C1260
230  TF(I6-1) 203,203,231                      C1270
231  TF(I6-LCP) 232,232,203                   C1280
232  TF(TX2T(J,I)-TCP(I6,I)) 234,245,233       C1290
233  T6=I6+1                                     C1300
    GO TO 231                                     C1310
234  TF(TX2T(J,I)-TCP(I6-1,I)) 235,245,240      C1320
235  T6=I6-1                                     C1330
    GO TO 230                                     C1340
240  CPB(J,I)=CPX(T6-1,I)+((CPX(I6,I)-CPX(T6-1,I))/(TCP(I6,I)-TCP(T6-1,  C1350
    I1)))*(TX2T(J,I)-TCP(I6-1,I))                C1360
    GO TO 280                                     C1370
245  CPB(J,I)=CPX(T6,I)                         C1380
280  CONTINUF                                    C1390
    T5=2                                         C1400
    T6=2                                         C1410
300  CONTINUE                                    C1420
310  TF(DMP) 355,355,320                      C1430
320  WRITE(6,330)                                C1440
330  FORMAT(/1X,32H PROPERTIES OF ABLATION MATERIAL/)  C1450
    WRITE(6,335)                                C1460
335  FORMAT(/5X,5HYK(I),9X,5HCP(I),9X,6HRHO(I)/)  C1470
    WRITE(6,340) (YK(I),CP(I),RHO(I),I=1,NP)      C1480
340  FORMAT(2X,1PF12.5,2X,1PF12.5,2X,1PE12.5)   C1490
    WRITE(6,345)                                C1500
345  FORMAT(//1X,32H PROPERTIES OF BACK-UP STRUCTURE/)  C1510
    WRITE(6,347)                                C1520
347  FORMAT(/5X,8HYKR(J,I),7X,RHCP(R,J,I),7X,8HRHOBX(I),7X,7HFMFB(I),8X,  C1530
    17HEMBR(I),9X,6HDXR(I)/)                    C1540
    DO 350 I=1,NMR                            C1550
    KL=NPM(I)                                C1560
    DO 349 J=1,KL                            C1570
    WRITE(6,348) XKR(J,I),CPR(J,I),RHOBX(I),FMFB(I),FMBB(I),DXB(I)        C1580
348  FORMAT(3X,1PF12.5,3X,1PE12.5,3X,1PE12.5,3X,1PF12.5,3X,1PE12.5,3X,1  C1590
    1PF12.5)                                C1600
349  CONTINUE                                 C1610
350  CONTINUE                                 C1620
355  RETURN                                     C1630
    END                                         C1640

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$IBFTC ABL
C      THIS SUBROUTINE DETERMINES THE MASS FLOW RATE FROM THE
C      ABLATING NODES
C      SUBROUTINE ABLATE
C
C      DIMENSION TITLE(12),HEADNG(12),XTDNT(12,12),TKC(20),XKC(20),
C      1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300),
C      2QRAD(300),VEL(300),XNPM(12),NKPR(12),NCPB(12),TXK(20,12),XK(20,12)
C      3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),FMB(12),EMBR(12),HXX(12)
C      4,GAPX(12),FTFST(12),RTEST(12),TEMDI(200),TX1(200),TX2(200),
C      5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),TR1(50),
C      6TR2(50),TUL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200),
C      7R(50),RHO(50),CP(50),DXP(12),XKB(10,12),CPB(10,12),XMNG(50),
C      8YK(50),AB(10,12),BB(10,12),CR(10,12),DB(10,12),SR(10,12),
C      9RP1(10,12),RP2(10,12),H(12),S(50),NPM(12)
C      DIMENSION TTUL(50),RHONY1(50),RHONY2(50),DRHO(50),TCP(20)
C
C      COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XRM,FMBR,
C      1FMB,XKPR,NCPB,TXK,XK,TCP,CPX,NPM,GAPX,FTFST,RTEST,TEMDI,TX1,
C      2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AR,RB,CR,DB,SR,
C      3RP1,RP2,TY,RHONY1,RHONY2,XMNG,RHO,CP,YK,XKR,CPB,DXR,DT,XLOST,
C      4TABL,TCHAR,TRFC,RHOV,PHOC,FRLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV,
C      5NP,NMR,NPRS,NPF,TTEST,TEMPI,TX0,TENV,HENV,FFNV,QLOSS,TLIM,TINT
C      COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,FRR1,ERRP,
C      1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ABLC,XMNC,H
C
C      XMT=0.0
C      LINT=TNT
C      KI=NP
C      TF(DMP) 8,8,3
C      3 WRITE(6,5)
C      5 FORMAT(//1X,29HMASS FLOW FROM ABLATING NODES//)
C      8 DO 200 KKI=LINT,NP
C          TF(IR1(KI)) 11,11,12
C      11 TF(TX1(KI)).LF.TABL) GO TO 9
C      12 TUL1(KI)=AMAX1(TUL1(KI),TX1(KI))
C          TP1(KI)=1
C          GO TO 20
C      9 TF(TX1(KI)-TABL) 10,10,20
C      10 RHONY1(KI)=RHOV
C          GO TO 50
C      20 TF(TUL1(KI)-TCHAR) 40,30,30
C      30 RHONY1(KI)=RHOC
C          GO TO 50
C      40 RHONY1(KI)=RHOV+(RHOV-RHOC)*((TUL1(KI)-TABL)/(TABL-TCHAR))
C      50 TF(IR2(KI)) 52,52,54
C      52 TF(TX2(KI)).LE.TABL) GO TO 56
C      54 TUL2(KI)=AMAX1(TUL2(KI),TX2(KI))
C          IR2(KI)=1
C          GO TO 70
C      56 TF(TX2(KI)-TABL) 60,60,70
C      60 RHONY2(KI)=RHOV
C          GO TO 95
C      70 TF(TUL2(KI)-TCHAR) 90,80,80
C      80 RHONY2(KI)=RHOC
C          GO TO 95
C      90 RHONY2(KI)=RHOV+(RHOV-RHOC)*((TUL2(KI)-TABL)/(TABL-TCHAR))

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95 DRHO(KI)=((RHOY1(KI)-RHOY2(KI))/DT)*DX	D0570
TF(KI-NP) 97,96,96	D0580
96 DRHO(KI)=DRHO(KI)/2.0	D0590
GO TO 98	D0600
97 IF(KI-INT) 96,96,98	D0610
98 IF(DRHO(KI)) 110,120,120	D0620
110 DRHO(KI)=0.0	D0630
120 XMT=XMT+DRHO(KI)	D0640
XMDG(KI)=XMT	D0650
IF(DMP) 190,190,150	D0660
150 WRITE(6,160) XMDG(KI),DRHO(KI),RHOY2(KI),RHOY1(KI)	D0670
160 FORMAT(1X,5HXMKG=,1PE12.5,2X,5HDRHO=,1PF12.5,2X,6HRHOY2=,1PE12.5,2	D0680
1X,6HRHOY1=,1PF12.5)	D0690
190 KI=KI-1	D0700
200 CONTINUE	D0710
RRETURN	D0720
FND	D0730

```
$IBFTC OXID          F0000
C                   F0010
C THIS SUBROUTINE CALCULATES THE HEATING RATE DUE TO COMBUSTION   F0020
C IT IS ASSUMED THAT OXYGEN AND CARBON REACT TO FORM CO ONLY.     F0030
C                   F0040
SUBROUTINE OXYDAT(XMDO,QOXID)           F0050
C                   F0060
QOXID=XMDO*4000.0/3600.0      F0070
QOXID=0.0
RFTURN
FND
```

```

$IBFTC SWUFT          F0000
C   THIS SUBROUTINE DETERMINES THE FORWARD TIME STEP TEMPFRAURES    F0010
C   BY SOLVING THE TRI-DIAGONAL MATRIX                                F0020
SUBROUTINF SWUFT(A,B,C,D,T,N,DMP)                                     F0030
DIMENSION A(200),B(200),C(200),D(200),T(200),CP(200),DP(200)        F0040
CP(1)=C(1)/B(1)                                                       F0050
DP(1)=D(1)/B(1)                                                       F0060
DO 100 I=2,N                                                          F0070
  CP(I)=C(I)/(B(I)-A(I)*CP(I-1))                                      F0080
  DP(I)=(D(I)-A(I)*DP(I-1))/(B(I)-A(I)*CP(I-1))                      F0090
100 CONTINUE
  T(N)=DP(N)
  NM1=N-1
  DO 200 J=1,NM1
    I=N-J
    T(I)=DP(I)-CP(I)*T(I+1)
200 CONTINUE
  TF(DMP) 300,300,250
250 WRITE(6,260)
260 FORMAT(//1X*43HCOEFFICIENTS CALCULATED BY SUBROUTINE SWUFT//)
  WRITE(6,270)
270 FORMAT(6X,5HCP(I),10X,5HD(P(I),10X,4HT(I)/)
  WRITE(6,275) (CP(I),DP(I),T(I),I=1,N)
275 FORMAT(2X,1PE12.5,2X,1PF12.5,2X,1PE12.5)
300 RRETURN
END

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$IBFTC REC                               G0000
C                                         G0010
C      THIS SUBROUTINE DETERMINES THE FRONT FACE LOCATION AND CHAR MASS   G0020
C      REMOVAL RATE                                                 G0030
C                                         G0040
C      SUBROUTINE RECESS(XMDC,XLOST,TREC,DT,RHOC,TS,SR,TX2,NREC,NRS,FRR5,   G0050
15X0,SDOT,DMP)                           G0060
C                                         G0070
C      DIMENSION TS(50),SR(50)                                G0080
1F(TX2-TREC) 10,20,20                      G0090
10 XMDC=0.0                                     G0100
XLOST=0.0                                      G0110
SDOT=0.0                                       G0120
GO TO 60                                       G0130
20 IF(NRS-1)25,25,21                         G0140
21 IF(NRS-NRFC) 22,22,25                     G0150
22 IF(TX2-TS(NRS)) 32,40,30                 G0160
25 WRITE(6,26) TX2                           G0170
26 FORMAT(1H0,75H THE RANGE OF THE SURFACE RECEDITION TABLE WAS EXCEEDED  G0180
1FD AT A TEMPERATURE OF ,1PE12.5)          G0190
FPR5=1.0                                      G0200
GO TO 60                                      G0210
30 NRS=NRS+1                                 G0220
GO TO 21                                      G0230
32 IF(TX2-TS(NRS-1)) 34,40,36               G0240
34 NRS=NRS-1                                 G0250
GO TO 20                                      G0260
36 SX=SR(NRS-1)+((SR(NRS)-SR(NRS-1))/(TS(NRS)-TS(NRS-1)))    G0270
1*(TX2-TS(NRS-1))                          G0280
GO TO 50                                      G0290
40 SX=SR(NRS)                                G0300
50 XLOST=300.0*SX*DT                         G0310
XMDC=(XLOST*RHOC)/DT                        G0320
SDOT=SX*300.0                                 G0330
1F(DMP) 60,60,52                            G0340
52 WRITE(6,54) SX,XLOST,XMDC                G0350
54 FORMAT(1H0,3HSX=,1PE12.5,3X,6HXLOST=,1PE12.5,3X,5HXMDC=,1PE12.5)  G0360
60 RRETURN                                    G0370
FND                                         G0380

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SIBFTC TEMP H0000
C   THIS SUBROUTINE DETERMINES THE INITIAL TEMPERATURE DISTRIBUTION H0010
C   IN THE HEAT SHIELD STRUCTURE H0020
C   SUBROUTINE TEMPD H0030
C   H0040
C   DIMENSION TITLE(12),HEADNG(12),XIDNT(12,12),TKC(20),XKC(20), H0050
1CPC(20),TKV(20),XKV(20),TCPV(20),CPV(20),TIME(300),QCON(300), H0060
2RAD(300),VEL(300),XNPM(12),NKPR(12),NCPR(12),TXK(20,12),XK(20,12) H0070
3,TCP(20,12),CPX(20,12),RHOBX(12),XBM(12),EMFB(12),EMBR(12),HXX(12) H0080
4,GAPX(12),FTEST(12),ATEST(12),TEMIDI(200),TX1(200),TX2(200), H0090
5TX2T(10,12),TUL1(200),TUL2(200),HX(50),TW(50),IR(50),IR1(50), H0100
6TR2(50),TIL(50),IEM(50),TY(200),A(200),B(200),C(200),D(200), H0110
7R(50),RH0(50),CP(50),DXR(12),XKR(10,12),CPB(10,12),XMDG(50), H0120
8YK(50),AB(10,12),RB(10,12),CR(10,12),DB(10,12),SR(10,12), H0130
9RB1(10,12),RRP(10,12),H(12),S(50),NPM(12) H0140
DIMENSION TTUL(50),RH0Y1(50),RH0Y2(50),DRHO(50),TCP(20) H0150
C   H0160
COMMON TKC,XKC,TCPC,CPC,TKV,XKV,TCPV,CPV,XNPM,RHOBX,XRM,EMBB, H0170
1EMFB,NKPB,NCPR,TXK,XX,TCP,CPX,NPM,GAPX,FTEST,ATEST,TEMIDI,TX1, H0180
2TX2,TX2T,TUL,TUL1,TUL2,IR,IR1,IR2,A,B,C,D,S,R,AB,BB,CR,DB,SB, H0190
3RR1,RR2,TY,RH0Y1,RH0Y2,XMDG,RHO,CP,YK,XKR,CPB,DXR,DT,XLOST, H0200
4TABL,TCHAR,TRFC,RHOV,RHOC,FLOW,FMV,EMC,H300,NKC,NCPC,NKV,NCPV, H0210
5NP,NMR,NPRS,NPF,TEST2,TEMPI,TX0,TENV,HENV,FENV,QLOSS,TLIM,TINT H0220
COMMON I1,I2,I3,I4,I5,I6,QIN,INT,DX,XMT,TL,VL,BL,DMP,FRR1,ERR2, H0230
1FRR3,FRR4,HV,VPT,CHARK,CHARC,ABLK,ABLCK,XMDC,H H0240
C   H0250
      X=0.0 H0260
      IF(TEST2) 300,100,200 H0270
100 DO 150 L=1,NPF H0280
      TX1(L)=TEMPI H0290
      TX2(L)=TEMPI H0300
      TUL1(L)=TX1(L) H0310
      TUL2(L)=TX2(L) H0320
      TEMDI(L)=TEMPI H0330
150 CONTINUE H0340
      DO 160 I=1,NMR H0350
      JN=NPM(I) H0360
      DO 155 M=1,JN H0370
      TX2T(M,I)=TEMPI H0380
155 CONTINUE H0390
160 CONTINUE H0400
      GO TO 320 H0410
200 DO 220 L=1,NP H0420
      TEMDI(L)=TX0+((TENV-TX0)/TL)*** H0430
      TX1(L)=TEMDI(L) H0440
      TX2(L)=TX1(L) H0450
      TUL1(L)=TX1(L) H0460
      TUL2(L)=TX1(L) H0470
      X=X+DX H0480
220 CONTINUE H0490
      L=NP+1 H0500
      DO 270 I=1,NMR H0510
      KJ=NPM(I) H0520
      DO 250 J=1,KJ H0530
      TEMDI(L)=TX0+((TENV-TX0)/TL)*** H0540
      TX1(L)=TEMDI(L) H0550
      TX2(L)=TEMDI(L) H0560

```

TX2T(J,I)=TEMPI(L)	H0570
X=X+DXB(I)	H0580
L=L+1	H0590
250 CONTINUE	H0600
X=X+(GAPX(I)/12.0)	H0610
270 CONTINUE	H0620
GO TO 320	H0630
C AN ARBITRARY TEMPERATURE DISTRIBUTION CAN BE READ IN FROM INPUT	H0640
C DATA IF TESTP IS A NEGATIVE NUMBER	H0650
300 WRITE(6,310)	H0660
310 FORMAT(1H0,79H THE VALUE OF TESTP WAS NEGATIVE, SUBROUTINE TEMPD SHOULD NOT HAVE BEEN CALLED.)	H0670
1H0,79H THE VALUE OF TESTP WAS NEGATIVE, SUBROUTINE TEMPD SHOULD NOT HAVE BEEN CALLED.)	H0680
FRR1=1.0	H0690
320 RETURN	H0700
FND	H0710

```

$IBFTC D0N2                                     T0000
C      THIS SUBROUTINE DETERMINES THE TEMPERATURE OF POINTS A FIXED      T0001
C      DISTANCE FROM A REFERENCE PLANE FROM THE TEMPERATURES CALCULATED   T0020
C      IN A VARYING THICKNESS                                              T0030
C
C      SUBROUTINE D0N2(XLOST,XARRAY,TARRAY,NA,XNODE,TEMP,XNODEV,KK,XLSTV,    T0040
C      1DX)
C
C      DIMENSION XARRAY(50),TARRAY(50),XNODE(50),TEMP(50),XNODEV(50)        T0050
C
C      K=0
C      DXT=0.0
C      DO 100 I=1,NA
C      IF(XLSTV.LE.DXT) GO TO 150
C      K=K+1
C100  DXT=DXT+DX
C150  KK=NA-K
C      XK=K
C      XNODEV(1)=XLSTV
C      TFMP(1)=TARRAY(1)
C      DO 200 I=1,KK
C      XNODE(I)=XK*DX-XLSTV
C      CALL DISCT3(XNODE(I),XARRAY,TARRAY,NA,TFMP(I+1))
C      XNODEV(I+1)=XK*DX
C200  XK=XK+1.0
C      RETURN
C      END

```

```

$IBFTC UINTRP
  SUBROUTINE UINTRP(X,XTBL,Y,YTBL,N,J)
  DIMENSION XTBL(50),YTBL(50)
  I=J
  TF(I.GT.N.OR.I.LT.2) T=?
  10 TF(XTBL(I-1).LE.X.AND.X.LT.XTBL(I)) GO TO 40
  TF(X.GT.XTBL(I)) GO TO 30
  20 T=I-1
  TF(I.GE.2) GO TO 10
  T=2
  GO TO 40
  30 T=I+1
  TF(I.LE.N) GO TO 10
  T=N
  40 FRACT=(X-XTBL(I-1))/(XTBL(I)-XTBL(I-1))
  Y=YTBL(I-1)+(YTBL(I)-YTBL(I-1))*FRACT
  RETURN
  END

```

```

$IBFTC ISOT
SUBROUTINE ISOTHM(DEPTH,TFMP,BOND,N,ANS)
DIMENSION DEPTH(1),TFMP(1)
ANS=-1.
K=N-1
DO 100 I=1,K
  IF(TEMP(I)-BOND)2,1,3
1  ANS=DFPTH(I)
  GO TO 100
2  IF(TEMP(I+1)-BOND)100,100,4
4  ANS=DFPTH(I+1)-(TEMP(I+1)-BOND)*(DEPTH(I+1)-DEPTH(I))/(TFMP(I+1)-
   1TFMP(I))
  GO TO 100
3  IF(TEMP(I+1)-BOND)5,100,100
5  ANS=(TEMP(I)-BOND)*(DFPTH(I+1)-DFPTH(I))/(TEMP(I)-TEMP(I+1))+DEPTH
   1(I)
100 CONTINUE
  IF(BOND.EQ.TFMP(N))ANS=DFPTH(N)
  RFTURN
END

```

K0000  
K0010  
K0020  
K0030  
K0040  
K0050  
K0060  
K0070  
K0080  
K0090  
K0100  
K0110  
K0120  
K0130  
K0140  
K0150  
K0160  
K0170  
K0180  
K0190

```

$IBFTC SAVE
  SUBROUTINE SAVE(SAVE1,SAVE2,SAVE3,USE,NX1,VALUE,DT,TFINAL,TIME,
  1THING)
    DIMENSION SAVF1(1),SAVE2(1),SAVE3(1)
    USE=0.0
    SAVE1(NX1)=VALUE
    NX2=NX1-1
    IF(NX2.EQ.0)NX2=3
    SAVE2(NX2)=VALUE
    NX3=NX2-1
    IF(NX3.EQ.0)NX3=3
    SAVE3(NX3)=VALUE
    IF((TIME.LT.(2.*DT)).OR.(TIME.GE.(TFINAL-3.*DT)))GO TO 4
    GO TO (1,2,3),NX1
1  IF(((ABS(SAVF2(1)-SAVE2(2))).LE..001).OR.((ABS(SAVE2(2)-SAVE2(3)))
1.I.E..001))GO TO 5
    IF(((SAVE2(1).LT.SAVF2(2)).AND.((SAVE2(2).GT.SAVE2(3))).OR.((SAVE2(1)
11).T.SAVF2(2)).AND.((SAVE2(2).LT.SAVE2(3))))USE=SAVE2(2)
5  THING=SAVE2(2)
    GO TO 4
2  IF(((ABS(SAVE3(1)-SAVE3(2))).LE..001).OR.((ABS(SAVE3(2)-SAVE3(3)))
2.I.E..001))GO TO 6
    IF(((SAVE3(1).LT.SAVF3(2)).AND.((SAVE3(2).GT.SAVE3(3))).OR.((SAVE3(1)
11).GT.SAVF3(2)).AND.((SAVE3(2).LT.SAVE3(3))))USE=SAVE3(2)
6  THING=SAVE3(2)
    GO TO 4
3  IF(((ABS(SAVE1(1)-SAVF1(2))).I.E..001).OR.((ABS(SAVE1(2)-SAVE1(3)))
3.I.E..001))GO TO 6
    IF(((SAVE1(1).LT.SAVF1(2)).AND.((SAVE1(2).GT.SAVE1(3))).OR.((SAVE1(1)
11).GT.SAVF1(2)).AND.((SAVF1(2).LT.SAVE1(3))))USE=SAVE1(2)
7  THING=SAVF1(2)
4  NX1=NX1+1
    IF(NX1.EQ.4)NX1=1
    RRETURN
  END

```

```
$IBFTC DISCT3          M0000
      SUBROUTINE DISCT3(XA,TABX,TABY,NY,ANS)    M0010
      DIMENSION TABX(1),TABY(1)                  M0020
      CALL DISSFR(XA,TABX,1,NY,2,NN)             M0030
      NNN=3                                     M0040
      CALL LAGRAN(XA,TABX(NN),TABY(NN),NNN,ANS) M0050
      RRETURN                                    M0060
      END                                       M0070
```

```

$IBFTC DISS
    SUBROUTINE DISSER (XA,TAB,I,NX, ID,NPX)          W0000
    DIMENSION TAB(2000)                                W0010
C     DIMENSION TAB(2000)                                W0020
    NPT=ID+1                                         W0030
    NPB=NPT/2                                         W0040
    NPU=NPT-NPB                                     W0050
    IF (NX-NPT)   10,5,10                           W0060
5   NPX=I                                           W0070
    RETURN                                         W0080
10  NLOW=I+NPB                                     W0090
    NUPP=I+NX-(NPU+1)                               W0100
    DO 15 II=NLOW,NUPP                            W0110
    NLOC=II                                         W0120
    IF (TAB(II)-XA)   15,20,20                     W0130
15  CONTINUE                                       W0140
    NPX=NUPP-NPB+1                                 W0150
    RETURN                                         W0160
20  NL=NLOC-NPB                                   W0170
    NU=NL+ID                                      W0180
    DO 25 JJ=NL,NU                                W0190
    NDIS=JJ                                         W0200
    IF (TAB(JJ)-TAB(JJ+1))   25,30,25           W0210
25  CONTINUE                                       W0220
    NPX=NL                                         W0230
    RETURN                                         W0240
    W0250
30  IF (TAB(NDIS)-XA)   40,35,35           W0260
35  NPX=NDIS-ID                                  W0270
    RETURN                                         W0280
40  NPX=NDIS+1                                  W0290
    RETURN                                         W0300
    END                                            W0310

```

```

$IBFTC LAGR          T0000
SUBROUTINE LAGRAN (XA,X,Y,N,ANS)      T0010
DIMENSION X(200),Y(200)                T0020
C DIMENSION X(200),Y(200)                T0030
SUM=0.0                                T0040
DO 3 I=1,N                            T0050
PROD=Y(I)                            T0060
DO 2 J=1,N                            T0070
A=X(I)-X(J)                          T0080
IF (A) 1,2,1                           T0090
1 B=(XA-X(J))/A                      T0100
PROD=PROD*B                         T0110
2 CONTINUE                           T0120
3 SUM=SUM+PROD                       T0130
ANS=SUM                               T0140
RETURN                               T0150
END                                  T0160

```

```

$IBFTC MORE
      DIMENSION TITLE(12),X(2000),Y1(2000),Y2(2000),Y3(2000),Y4(2000)
      RFWIND 11
      RFAD(11) (TITLE(I),I=1,12)
      RFAD(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      Y3(1)=Y3(1)*12.+Y1(1)
      Y4(1)=Y4(1)*12.+Y1(1)
      I=2
 30  READ(11)X(I),Y1(I),Y2(I),Y3(I),Y4(I)
      IF(X(I)-5001.)10,20,20
 10  Y3(I)=Y3(I)*12.+Y1(I)
      Y4(I)=Y4(I)*12.+Y1(I)
      I=I+1
      GO TO 30
 20  NPLOT=I-1
      YM1=Y1(1)
      YM2=Y2(1)
      YM3=Y3(1)
      YM4=Y4(1)
      DO 40 K = 2 , NPLOT
      IF (Y1(K).GT.YM1) YM1 = Y1(K)
      IF (Y2(K).GT.YM2) YM2 = Y2(K)
      IF (Y3(K).GT.YM3) YM3 = Y3(K)
      IF (Y4(K).GT.YM4) YM4 = Y4(K)
 40  CONTINUE
 1000 FORMAT(1H1,(12A6))
      CALL ACCEND(X,Y1,Y2,Y3,Y4,NPLOT)
      XMAX=X(NPLOT)
      CALL APLOT (X,Y1,XMAX,YM1,TITLE,NPLOT)
      CALL BPLOT (X,Y2,XMAX,YM2,TITLE)
      CALL CPLOT (X,Y3,Y4,XMAX,YM3,YM4,TITLE,Y1)
      WRITE(6,1000)(TITLE(I),I=1,12)
      WRITE(6,1001)(X(I),Y1(I),Y2(I),Y3(I),Y4(I),I=1,NPLOT)
 1001 FORMAT(5E20.8)
      WRITE(6,1002)XMAX,YM1,YM2,YM3,YM4,NPLOT
 1002 FORMAT(//6H XMAX=F10.4,5H YM1=F10.4,5H YM2=F10.4,5H YM3=F10.4,5H
      YM4=F10.4,2X6HNPLOT=I4)
      RFAD(11) (TITLE(I),I = 1,12)
      RFAD(11)X(1),Y1(1),Y2(1),Y3(1),Y4(1)
      I=2
      IF(X(1)-5001.)30,50,50
 50  WRITE(6,1003)(TITLE(I),I=1,12)
 1003 FORMAT(///12A6)
      RETURN
      END

```

```

$IBFTC ACCEN          P0000
      SUBROUTINE ACCEND(X,Y,A,B,C,N)          P0010
      DIMENSION X(1),Y(1),A(1),B(1),C(1)          P0020
      K=1          P0030
101  SMALL=X(K)          P0040
      DO 100 I=K,N          P0050
      DUMY=X(I)          P0060
      SMALL=AMIN1(SMALL,DUMY)          P0070
      IF(SMALL.EQ.X(I))INDEX=I          P0080
100  CONTINUE          P0090
      X(INDEX)=X(K)          P0100
      X(K)=SMALL          P0110
      SAVE=Y(K)          P0120
      Y(K)=Y(INDEX)          P0130
      Y(INDEX)=SAVE          P0140
      SAVEA=A(K)          P0150
      A(K)=A(INDEX)          P0160
      A(INDEX)=SAVEA          P0170
      SAVEB=B(K)          P0180
      B(K)=B(INDEX)          P0190
      B(INDEX)=SAVER          P0200
      SAVEC=C(K)          P0210
      C(K)=C(INDEX)          P0220
      C(INDEX)=SAVEC          P0230
      K=K+1          P0240
      IF(K.EQ.N)RETURN          P0250
      GO TO 101          P0260
      END          P0270

```

```

$IBFTC APLOT
  SUBROUTINE APLOT (X,Y,XLT M,YLT M,TITLE,IPL OT)
  DIMENSION X(300),YTITL E(10),XTITLE(10)
  DIMENSION TITLE(12),Y(300),ALONGY(7)
  COMMON /APC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,TFIX
  DATA (XTITLE(I),I=1,10)/38H           TIME (SEC.)    /
  DATA (YTITL E(I),I=1,10)/38H          SURFACE RECESSSION (IN.)   /
  ZERO=0.0
  ALLOW(1)=50.
  ALLOW(2)=100.
  ALLOW(3)=250.
  ALLOW(4)=500.
  ALLOW(5)=1000.
  ALLOW(6)=2500.
  ALLOW(7)=5000.
  NPLOT=IPL OT
  DO 10 I=1,7
  II=I
  IF(XLT M- ALLOW(I)) 20,20,10
10  CONTINUE
30  WRITE (6,1000) XLIM,YI IM
1000 FORMAT(//7H APLOT CANNOT BE DONE BECAUSE EITHER XLT M EXCEEDS 50
      100. OR YLT M EXCEEDED 5. /6H XI IM=F12.5,5X,6H YLT M=E12.5 // 19H WF
      2NOW GO TO BPLOT // )
      RETURN
20  YMAX= ALLOW(1)
  1FIX=II
  DO 40 I=1,4
  IT=I
  IF(YLT M *100. -ALLOW(I) )50,50,40
40  CONTINUE
  GO TO 30
50  YMAX =ALLOW(IT) /100.
  CALL RSTPRM
  CALL GRDGN (123,1023,24,024,18,18,5,5)
  CALL PLOT1 (1,1,ZERO,XMAX,ZERO,YMAX,X,Y,NPLOT,1,1H/)
  ALONGX(1)=0.0
  ALONGY(1)=0.0
  DO 60 I=1,6
  CALL LABELX (ALONGX(I),1)
  CALL LABELY (ALONGY(I),1)
  ALONGX(I+1)= ALONGX(I) +.2* XMAX
60  ALONGY(I+1)= ALONGY(I) +.2* YMAX
  CALL PRNT(200,975,12,0,38,XTITLE)
  CALL PRINT(47,200,0,12,38,YTITL E)
  CALL DMPBNF
  RETURN
END

```

```

$IBFTC PLOT
      SUBROUTINE PPI OT (X,Y,XLT M,YLT M,TITLE)
      DIMENSION X(300),Y(300),YTITLF(10),ALONGY(7),XTITLE(10)
      DIMENSION TITL E(12)
      COMMON /APC / ALLOW(7),ALONGX(7),NPLOT,ZERO,XMAX,TFIX
      DATA (XTITLE(I),I=1,10)/3AH          TIME (SEC.)
      DATA (YTITLE(I),I=1,10)/3AH          BONDLINE TEMPERATURF (R)
      ALONGY(1)=0.0
      DO 10 I=1,7
      TT=I
      IF(YLT M -ALLOW(I)) 20,20,10
10  CONTINUE
      WRITE (6,1000) YLIM
1000 FORMAT(/// 3TH PPI OT WILL NOT BE DONE BECAUSE YLT M= E12.5 ////)
      RETURN
20  YMAX =ALLOW(JT)
      CALL RSTFRM
      CALL GRIDGN(123,1023,24,924,1B,1B,5,5 )
      CALL PLOTT (1,1,ZERO,XMAX,ZERO,YMAX,X,Y, NPLOT,1, 1H/ )
      DO 30 I=1,6
      CALL LABELX (ALONGX(I),1)
      CALL LABELY (ALONGY(I),1)
30  ALONGY(I+1) = ALONGY(I) + .2* YMAX
      CALL PRINT(200,975,12,0,3B,XTITLE)
      CALL PRINT(47,200,0,12,3B,YTITLF)
      CALL PRNT(123,1000,12,0,72,TITLE)
      CALL DMPLUF
      RETURN
END

```

R0000  
R0010  
R0020  
R0030  
R0040  
R0050  
R0060  
R0070  
R0080  
R0090  
R0100  
R0110  
R0120  
R0130  
R0140  
R0150  
R0160  
R0170  
R0180  
R0190  
R0200  
R0210  
R0220  
R0230  
R0240  
R0250  
R0260  
R0270  
R0280

```

$IBFTC CPLOT
SUBROUTINE CPLOT (X,Y1,Y2,XLIM,YLIM1,YLIM2,TITLEF, Y)
DIMENSION X(300),Y1(300),Y2(300),YTITLE(10),YY(2000),XTITLE(10)      S0000
DIMENSION TITL(E(12),Y(300),ALONGY(7)                                     S0010
DIMENSION CURVE(1),VRUG(4),HRUG(7)                                       S0020
COMMON /ARC / ALLOW(7),ALONGX(7),NPL0T,ZERO,XMAX,TFIX                  S0030
DATA (VRUG(I),I=1,4) / 100.0,50.0,20.0,10.0 /                           S0040
DATA (HRUG(I),I=1,7) / 1.0,2.0,5.0,10.0,20.0,50.0,100.0 /              S0050
DATA (XTITLE(I),I=1,10)/3AH                                             TIME (SEC.) / S0060
DATA (YTITLE(I),I=1,10)/3AH                                             DISTANCE (IN.) / S0070
DATA ONE/4H1060/,TWO/4H1460/                                           S0080
DATA ONE/4H1060/,TWO/4H1460/                                           S0090
S0100
S0110
S0120
C *** FOUR (4) CHARACTERS ARE ALLOWED FOR CURVE(1)
CURVE(1)=ONE                                         S0130
HFACTR=HRUG(TFIX)                                     S0140
SYMROLE=WON                                         S0150
YB1G =AMAX1 (YLIM1,YLIM2 )                         S0160
NCURVF =1                                         S0170
DO 1 I=1,NPL0T
1 YY(I)= Y1(I)                                      S0180
DO 7 I=1,4
    TI= I
    IF(YBTG*100. .-ALLOW(T))6,6,7
7 CONTINUE
    WRITE (6,1000) YLIM1,YLIM2
1000 FORMAT (// 3AH CPLOT WILL NOT BE DONE BECAUSE YLIM1=E12.5,10H OR
1YLIM2=E12.5 //++)
    RETURN
6 YMAX =ALLOW (TI)/100.
VFACTR=VBUG(IT)
CALL RSTFPM
CALL GRTDGN (123,1023,24.024,18,18,5,5)
J=1
70 DO 10 I=J,NPL0T
    TI= I
    IM1 =T-1
    IF( YY(I)-Y(T) )20,10,10
10 CONTINUE
    N0PT=NPL0T-J+1
    LI=J + N0PT/2
    TVLOC=(YMAX-YY(LL))*18.*VFACTR +24. -4.
    THLOC= X(LL)*18. /HFACTR +123. -48.
    CALL PRINT(IHI OC,TVLOC, A,0+4,CURVE)
    CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),N0PT ,1,SYMROI )
    IF (NCURVF-1 ) 90,85,90
85 DO 86 I=1,NPL0T
86 YY(I)=Y2(T)
    CURVE(1)=TWO
    SYMROLE=T00
    NCURVF = 2
    J=1
    GO TO 70
20 NPT=IT-J
    LL=J + NPT/2
    TVLOC=(YMAX-YY(LL))*18.*VFACTR +24. -4.
    THLOC= X(LL)*18. /HFACTR +123. -48.
    CALL PRINT(IHI OC,TVLOC, A,0+4,CURVE)

```

```

CALL PLOT1(1,1,ZERO,XMAX,ZERO,YMAX,X(J),YY(J),NPT,1,SYMPOL)      S0570
DO 50 IJ= II, NPLOT
JJ= IJ
TF(YY(IJ)- Y(TJ) )50,40,40
50 CONTINUF
IF(NCURVE-1) 90,85,90
40 JI= JJ
GO TO 70
90 AIONGY(1)=0.0
DO 100 I=1,6
CALL LARELX(AIONGY(I), 1)
CALL LARELY(AIONGY(I),1)
100 AIONGY(I+1)=AIONGY(I) + .2*YMAX
CALL PRINT(200,975,12,0,38,XTITLE)
CALL PRINT(47,200,0,12,38,YTITLE)
CALL PRINT(123,1000,12,0,72,TITLE)
CALL DMPLIF
RETURN
END

```

## APPENDIX D

### PROGRAM TERMINOLOGY

<u>FORTRAN</u>	<u>Description</u>
A	"A" coefficient in matrix, single subscript
AB	"A" coefficient in matrix, double subscript
ABLC	specific heat of material at TABL
ABLK	thermal conductivity of material at TABL
B	"B" coefficient in matrix, single subscript
BB	"B" coefficient in matrix, double subscript
BL	Total thickness of backup structure
BLTEM	value of 1460 isotherm depth from previous time step
BTEST	test to determine mode of heat transfer out of back surface of backup materials
C	"C" coefficient in matrix, single subscript
CB	"C" coefficient in matrix, double subscript
CHARC	specific heat of material at TCHAR
CHARK	thermal conductivity of material at TCHAR
CP	specific heat of a node in ablation material
CPB	specific heat of backup material node
CPC	specific heat values in char specific heat table
CPV	specific heat values in virgin specific heat table
CPX	specific heat values in backup material specific heat tables
D	"D" coefficient in matrix, single subscript
DB	"D" coefficient in matrix, double subscript
DELT	time step in the time step table

<u>FORTRAN</u>	<u>Description</u>
DMP	test used for dumping (DMP = 0 skip dump, DMP = 1.0 start dumping)
DRH $\phi$	local mass flow rate of ablation gas
DT	time step from the time step table in hours
DTS	time step from time step table in seconds
DX	thickness of a node in the ablation material
DXB	thickness of a node in a backup structure material
DXV	variable ablation node thickness $\left( = \frac{VLV}{NP - 1} \right)$
DXX	fixed ablation material node thickness $\left( = \frac{VLI}{NP - 1} \right)$
EMBB	emissivity of back surface of each material in backup
EMC	char material emissivity
EMFB	emissivity of front surface of each material in backup
EMV	virgin material emissivity
EMX	emissivity of front surface of ablation material
END	code word for plot routine
ERR1	Control numbers for printing error statements when an input or calculational mistake is made
ERR2	
ERR3	
ERR4	
FBL $\phi$ W	blowing efficiency in reducing convective heating
FC $\phi$ NV	factor to correct convective heating rate for various body locations
FENV	emissivity - view factor product to cabin interior
FRAD	factor to correct radiative heating rate for various body locations
FTEST	test to determine mode of heat transfer into front surface of backup materials

<u>FORTRAN</u>	<u>Description</u>
FV	view factor for external environment
G	defined by FORTRAN statement
GAPX	gap width between backup materials
H	film coefficient between backup materials
H300	enthalpy of air at 300° K
HEAD	any 72 alphanumeric characters used to identify problems being run - printed at top of first page of output
HEADNG	any 72 alphanumeric characters used to identify each input section
HENV	film coefficient to cabin environment
HTX	total enthalpy
HV	heat of degradation of virgin material
HW	wall enthalpy computed from enthalpy - temperature table
HX	enthalpy values in enthalpy table
IEM	test used to determine if front surface is virgin or char for using proper emissivity
IPRC	variable print frequency in time-step table
IPRCT	present print control number
IR	test to determine if node temperature is greater than TABL
IR1	test used in determining node density at TX1 temperature
IR2	test used in determining node density at TX2 temperature
NCASE	number of problems to be run
NCPB	number of points in each backup material specific heat table
NCPC	number of points in char specific heat temperature table
NCPV	number of points in virgin specific heat temperature table
NKC	number of points in char thermal conductivity - temperature table

<u>FORTRAN</u>	<u>Description</u>
NKPB	number of points in each backup material thermal conductivity table
NKV	number of points in virgin thermal conductivity temperature table
NMB	number of materials in backup structure
NP	number of node points in ablation material
NPBS	total number of node points in backup structure
NPF	total number of points in heat shield structure (NP + NPBS)
NPL $\phi$ T	output plot control number
NPM	number of nodes per material in backup
NHP	number of points in enthalpy - temperature table
NPTT	number of points in time-step table
NREC	number of points in surface recession - temperature or time table
NTRAPT	number of points in trajectory input table
NXA	
NXB	
NXC	
NXD	
NXE	
QBL $\phi$ CK	amount of convective heat blocked due to mass injection into boundary layer
QC $\phi$ N	trajectory table convective heating rates
QC $\phi$ NX	cold wall convective heat rate at present time step
QHW	hot wall convective heat rate without blowing
QIN	net heat flux into front surface
QL $\phi$ SS	boundary condition for heat transfer to cabin interior
Q $\phi$ XID	heating rate due to combustion

<u>FORTRAN</u>	<u>Description</u>
QRAD	trajectory table radiative heating rates
QRADX	radiative heat flux at present time step
QUIT	code word for plot routine
R	thermal resistance due to conductivity between nodes in the ablation material
RB1	thermal resistance due to conductivity between past and present node in backup material
RB2	thermal resistance due to conductivity between present and forward node in backup material
RH $\phi$	density of an ablation material node
RH $\phi$ BX	density of individual materials in backup
RH $\phi$ C	mature char material density
RH $\phi$ V	virgin ablation material density
RH $\phi$ Y1	density of node at past time step
RH $\phi$ Y2	density of node at present time step
S	thermal capacity of a node in the ablation material
SD $\phi$ T	surface recession rate
SAVEIT	depth of 1060 isotherm at any given time
SAVEXX	time corresponding to maximum depth of 1460 isotherm
SAVX	time corresponding to maximum depth of 1060 isotherm
SAVY1	surface recession depth at maximum 1060 isotherm depth
SAVY2	bondline temperature at maximum 1060 isotherm depth
SAVY3	term that will contain maximum depth of 1060 isotherm
SAVY4	depth of 1460 isotherm at maximum 1060 isotherm depth
SAVY1X	surface recession depth at maximum 1460 isotherm depth
SAVY2X	bondline temperature at maximum 1460 isotherm depth

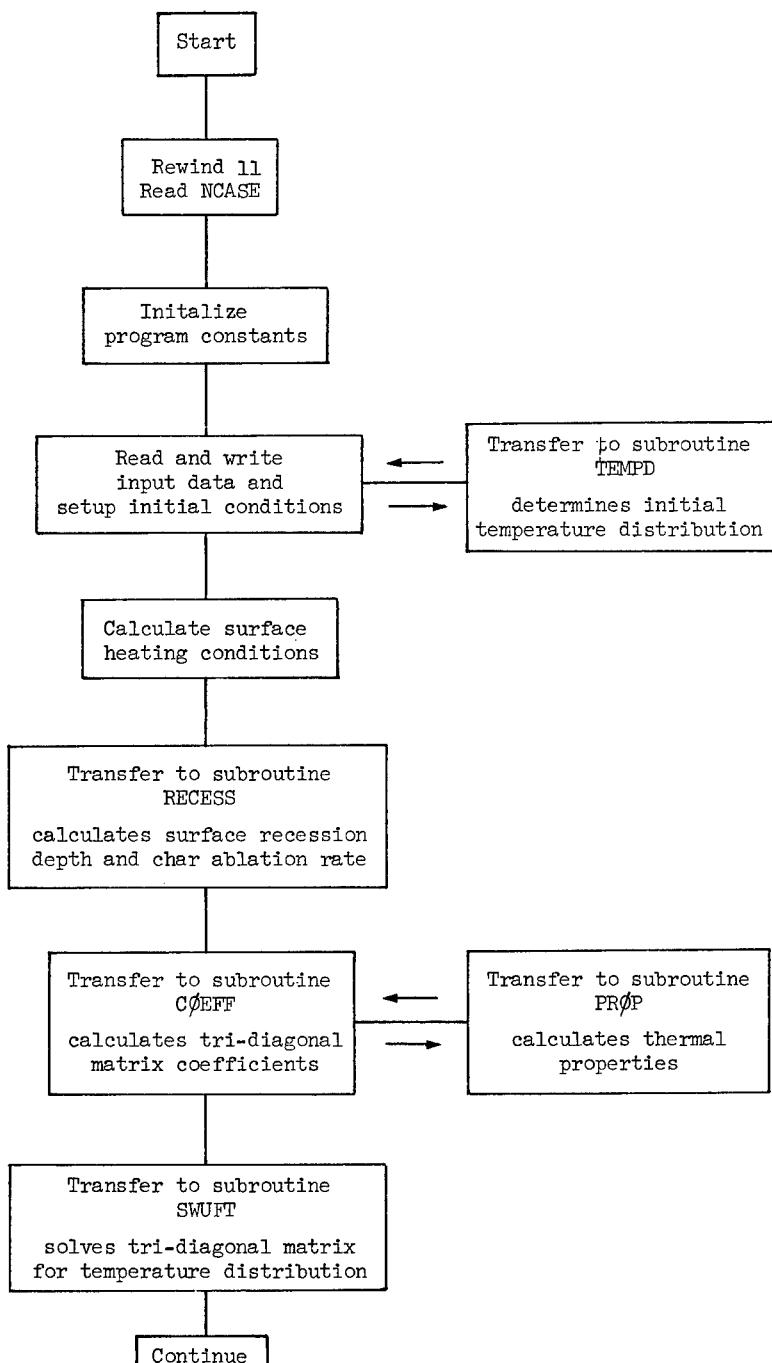
<u>FORTRAN</u>	<u>Description</u>
SAVY3X	depth of 1060 isotherm at maximum 1460 isotherm depth
SAVY4X	term that will contain maximum depth of 1460 isotherm
SR	surface recession values in surface recession table
T	present time
TABL	temperature at which ablation starts
TCHAR	temperature at which ablation stops
TCP	temperature values in backup material specific heat tables
TCPC	temperature values in char specific heat table
TCPV	temperature values in virgin specific heat table
TEMDI	arbitrary initial temperature distribution values
TEMPI	constant initial temperature distribution value
TENV	interior cabin temperature
TEST2	test to determine proper heat shield initial temperature distribution
TDMP	time to start dumping or printing information used in checkout of program (sets DMP = 1.0)
TIME	trajectory table time values
TINT	starting time of problem
TITLE	control card used for reading in new data for successive problems
TKC	temperature values in char thermal conductivity table
TKV	temperature values in virgin thermal conductivity table
TL	total thickness of heat shield structure (VL + BL)
TLIM	time limit of problem
TREC	surface temperature or time at which char removal is to start
TS	temperature or time values in surface recession table
TTABLE	time values in time-step table

<u>FORTRAN</u>	<u>Description</u>
TTUL	equals TUL if VPT = 0 or equals TX2 if VPT = 1 - used in computing char properties
TUL	maximum value of TX1 and TX2
TULL	maximum TX1 values - used in computing gas ablation rate
TUL2	maximum TX2 values - used in computing gas ablation rate
TV	sink temperature of external environment
TW	temperature values in enthalpy table
TX1	temperature of nodes at past time step
TX2	temperature of nodes at present time step
TX2C	temperature at fixed locations in ablation material as defined by XC
TX2T	temporary storage of TX2 temperatures for computing thermal properties
TXK	temperature values in backup material thermal conductivity tables
TX $\phi$	initial temperature at front surface of heat shield for computing linear temperature gradient
TY	temperature distribution at forward time step
VEL	trajectory table velocity values
VELX	trajectory velocity at present time step
VL	initial virgin material thickness
VLI	initial ablation material thickness
VLTEM	value of 1060 isotherm depth from previous time step
VLV	variable ablation material thickness
VPT	test to determine if properties are irreversible with temperature
WEKEEP	depth of 1460 isotherm at any time
XBM	thickness of individual materials in backup
XC	fixed location of nodes in the ablation material
XI	node number

<u>FORTRAN</u>	<u>Description</u>
XIDNT	any 72 alphanumeric characters to identify each material
XK	thermal conductivity values in backup material thermal conductivity table
XKB	thermal conductivity of backup material node
XKC	thermal conductivity in char thermal conductivity table
XKV	thermal conductivity value in virgin thermal conductivity table
XL $\phi$ ST	amount of solid ablation material lost in a time step due to surface movement
XLSTI	distance from original surface to present front surface location, inches
XLSTV	distance from original surface to present front surface location, feet
XMDC	mass loss rate of char
XMDG	mass gas ablation rate due to pyrolysis of virgin material
XMD $\phi$	mass flux rate of oxygen to surface
XMDT	total ablation rate
XNP	number of nodes in ablation material
XNPM	number of nodes per backup material
XPL $\phi$ T	time to be written on tape and plotted
XV	location of nodes in variable ablation material thickness
YK	thermal conductivity of a node in ablation material
YPL $\phi$ T1	recession depth to be written on tape and plotted
YPL $\phi$ T2	bondline temperature to be written on tape and plotted
YPL $\phi$ T3	1060 isotherm depth to be written on tape and plotted
YPL $\phi$ T4	1460 isotherm depth to be written on tape and plotted
ZZZ	ratio to determine when the limiting value of heat blockage has been reached

APPENDIX E

GENERAL FLOW CHART



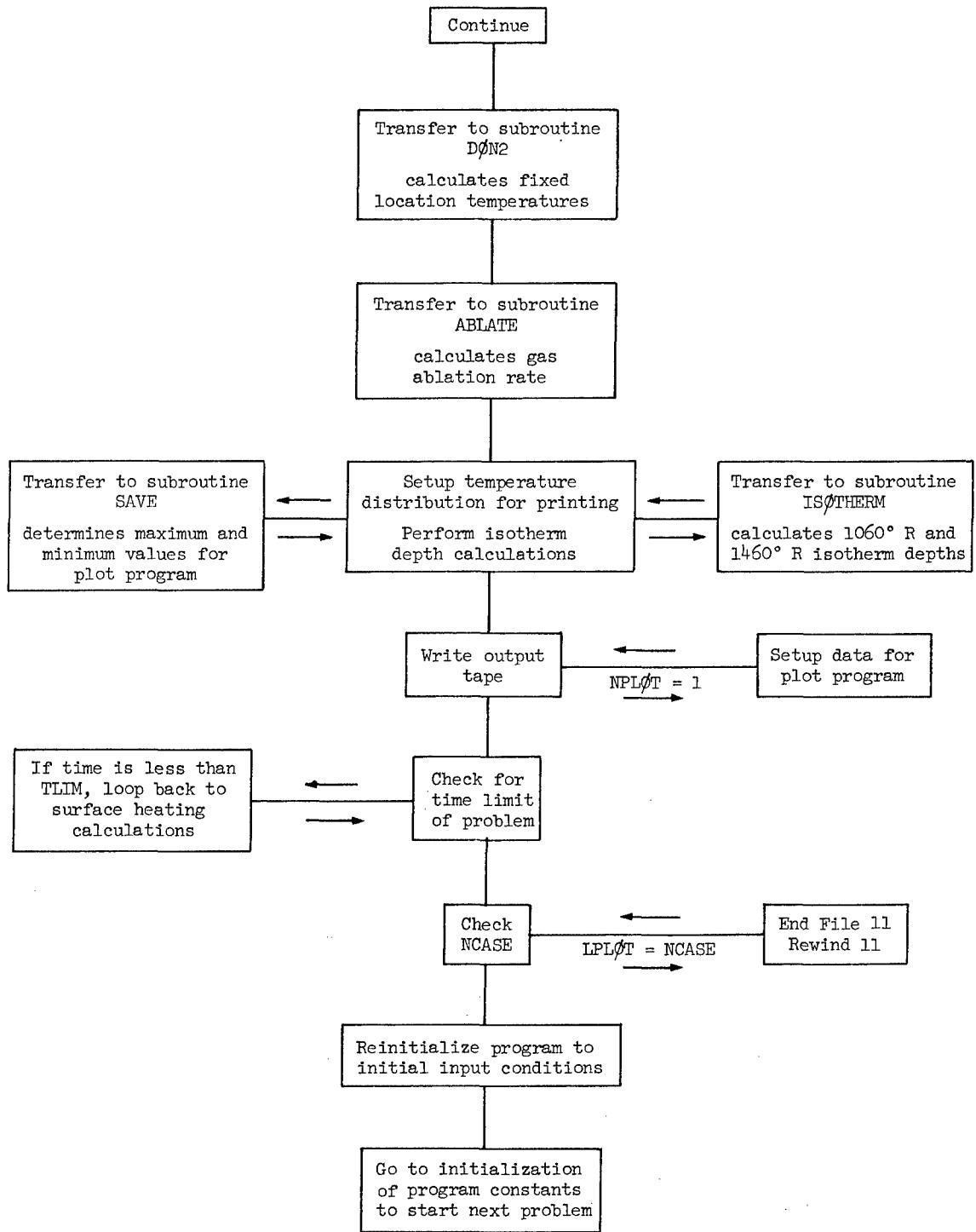


TABLE I.—SAMPLE PROBLEM INPUT

(a) Coding sheet

FORTRAN STATEMENT		CONTINUATION	SEQUENCE	
STATEMENT NUMBER	LOCATION	OPERATION	VARIABLE FIELD	COMMENTS
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NOTE: WRITE NUMBERS 10, LETTERS I, Q, U, G, Z, C, SYMBOLS /, \*,

TABLE I.— SAMPLE PROBLEM INPUT - Continued

(a) Coding sheet

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STATEMENT NUMBER	CONTINUATION NUMBER	OPERATION	VARIABLE FIELD	SEQUENCE NUMBER	COMMENTS
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7393 7397 7401 7405 7409 7413 7417 7421 7425 7429 7433 7437 7441 7445 7449 7453 7457 7461 7465 7469 7473 7477 7481 7485 7489 7493 7497 7501 7505 7509 7513 7517 7521 7525 7529 7533 7537 7541 7545 7549 7553 7557 7561 7565 7569 7573 7577 7581 7585 7589 7593 7597 7601 7605 7609 7613 7617 7621 7625 7629 7633 7637 7641 7645 7649 7653 7657 7661 7665 7669 7673 7677 7681 7685 7689 7693 7697 7701 7705 7709 7713 7717 7721 7725 7729 7733 7737 7741 7745 7749 7753 7757 7761 7765 7769 7773 7777 7781 7785 7789 7793 7797 7801 7805 7809 7813 7817 7821 7825 7829 7833 7837 7841 7845 7849 7853 7857 7861 7865 7869 7873 7877 7881 7885 7889 7893 7897 7901 7905 7909 7913 7917 7921 7925 7929 7933 7937 7941 7945 7949 7953 7957 7961 7965 7969 7973 7977 7981 7985 7989 7993 7997 8001 8005 8009 8013 8017 8021 8025 8029 8033 8037 8041 8045 8049 8053 8057 8061 8065 8069 8073 8077 8081 8085 8089 8093 8097 8101 8105 8109 8113 8117 8121 8125 8129 8133 8137 8141 8145 8149 8153 8157 8161 8165 8169 8173 8177 8181 8185 8189 8193 8197 8201 8205 8209 8213 8217 8221 8225 8229 8233 8237 8241 8245 8249 8253 8257 8261 8265 8269 8273 8277 8281 8285 8289 8293 8297 8301 8305 8309 8313 8317 8321 8325 8329 8333 8337 8341 8345 8349 8353 8357 8361 8365 8369 8373 8377 8381 8385 8389 8393 8397 8401 8405 8409 8413 8417 8421 8425 8429 8433 8437 8441 8445 8449 8453 8457 8461 8465 8469 8473 8477 8481 8485 8489 8493 8497 8501 8505 8509 8513 8517 8521 8525 8529 8533 8537 8541 8545 8549 8553 8557 8561 8565 8569 8573 8577 8581 8585 8589 8593 8597 8601 8605 8609 8613 8617 8621 8625 8629 8633 8637 8641 8645 8649 8653 8657 8661 8665 8669 8673 8677 8681 8685 8689 8693 8697 8701 8705 8709 8713 8717 8721 8725 8729 8733 8737 8741 8745 8749 8753 8757 8761 8765 8769 8773 8777 8781 8785 8789 8793 8797 8801 8805 8809 8813 8817 8821 8825 8829 8833 8837 8841 8845 8849 8853 8857 8861 8865 8869 8873 8877 8881 8885 8889 8893 8897 8901 8905 8909 8913 8917 8921 8925 8929 8933 8937 8941 8945 8949 8953 8957 8961 8965 8969 8973 8977 8981 8985 8989 8993 8997 9001 9005 9009 9013 9017 9021 9025 9029 9033 9037 9041 9045 9049 9053 9057 9061 9065 9069 9073 9077 9081 9085 9089 9093 9097 9101 9105 9109 9113 9117 9121 9125 9129 9133 9137 9141 9145 9149 9153 9157 9161 9165 9169 9173 9177 9181 9185 9189 9193 9197 9201 9205 9209 9213 9217 9221 9225 9229 9233 9237 9241 9245 9249 9253 9257 9261 9265 9269 9273 9277 9281 9285 9289 9293 9297 9301 9305 9309 9313 9317 9321 9325 9329 9333 9337 9341 9345 9349 9353 9357 9361 9365 9369 9373 9377 9381 9385 9389 9393 9397 9401 9405 9409 9413 9417 9421 9425 9429 9433 9437 9441 9445 9449 9453 9457 9461 9465 9469 9473 9477 9481 9485 9489 9493 9497 9501 9505 9509 9513 9517 9521 9525 9529 9533 9537 9541 9545 9549 9553 9557 9561 9565 9569 9573 9577 9581 9585 9589 9593 9597 9601 9605 9609 9613 9617 9621 9625 9629 9633 9637 9641 9645 9649 9653 9657 9661 9665 9669 9673 9677 9681 9685 9689 9693 9697 9701 9705 9709 9713 9717 9721 9725 9729 9733 9737 9741 9745 9749 9753 9	

NOTE: WRITE NUMBERS 10, LETTERS 19 UGZC, SYMBOLS /., \*

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TABLE I.- SAMPLE PROBLEM INPUT - Concluded

(a) Coding sheet

STATEMENT NUMBER	CONTINUATION NUMBER	FORTRAN STATEMENT		SEQUENCE NUMBER	OPERATION	FIELD	VARIABLE	COMMENTS
		LOCATION	DATA					
+2.000.0	+00	+5728.0	+00	+2100.0	+00	+5851.0	+00	+2200.0
+2.300.0	+00	+6078.0	+00	+2400.0	+00	+6186.0	+00	+2500.0
+2.600.0	+00	+6395.0	+00	+2700.0	+00	+6497.0	+00	+2800.0
+2.900.0	+00	+6699.0	+00	+3000.0	+00	+6805.0	+00	+3100.0
+3.200.0	+00	+7050.0	+00	+3300.0	+00	+7175.0	+00	+3400.0
+3.500.0	+00	+7480.0	+00	+3600.0	+00	+7430.0	+00	+3700.0
+3.800.0	+00	+7970.0	+00	+3900.0	+00	+8120.0	+00	+4000.0
+4.100.0	+00	+8500.0	+00	+4200.0	+00	+8700.0	+00	+4300.0
+4.400.0	+00	+8900.0	+00	+4500.0	+00	+9150.0	+00	+4600.0

MSC Form 244 (Apr 1962)

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NOTE: WRITE NUMBERS 10, LETTERS IΦUGZC, SYMBOLS /, \*,

TABLE I.- SAMPLE PROBLEM INPUT

(b) Fortran data card listing

**1** TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY

+600.0	+00	+0.0	+00	2	1
+0.0	+00	+0.1	+00	100	
+600.0	+00	+0.1	+00	100	
+1.0	+00	+1.0	+00		
 TYPICAL CHARRING ABLATION MATERIAL PROPERTIES					
+1060.0	+00	+1460.0	+00	+0.0	+00 +34.0 +00 +20.0 +00 +0.00 +00
+0.65	+00	+0.75	+00 +129.06	+00 +1.50	+00 +250.0 +00 +0.0 +00
+1.0	+00	+0.0	+00 +0.12	+00 +0.43	+00 +0.070 +00 +0.43 +00
31	2	2	0	2	2
+1460.0	+00	+0.12	+00 +1.0	+04 +0.12	+00
+1460.0	+00	+0.43	+00 +1.0	+04 +0.43	+00
+360.0	+00	+0.065	+00 +460.0	+00 +0.065	+00 +560.0 +00 +0.0655 +00
+660.0	+00	+0.066	+00 +760.0	+00 +0.0672	+00 +860.0 +00 +0.0684 +00
+460.0	+00	+0.069	+00 +1060.0	+00 +0.070	+00 +1160.0 +00 +0.070 +00
+360.00	+00	+0.43	+00 +1100.0	+00 +0.43	+00
+0.0	+00	+9.0	-04 +600.0	+00 +9.0	-04
 NO TRAJECTORY - Q=95 RTU/SEC-SOFT					
<b>2</b>					
+0.0	+00	+95.0	+00 +0.0	+00 +2.925	+04
+600.0	+00	+95.0	+00 +0.0	+00 +2.925	+04
1	3	+0.1	+00		
+3.0	+00				
9	2				
 BACKUP MATERIAL 0.1 INCHES THICK					
+360.0	+00	+0.065	+00 +460.0	+00 +0.065	+00 +560.0 +00 +0.0655 +00
+660.0	+00	+0.066	+00 +760.0	+00 +0.0672	+00 +860.0 +00 +0.0684 +00
+460.0	+00	+0.069	+00 +1060.0	+00 +0.07	+00 +1160.0 +00 +0.07 +00
+360.00	+00	+0.43	+00 +1100.0	+00 +0.43	+00
+34.0	+00	+0.1	+00 +0.9	+00 +0.9	+00
+0.0	+00	+0.0	+00 +0.0	+00 +0.0	+00
 HEAT TRANSFER TO CAPIN ENVIRONMENT - HENV=0.0					
+560.0	+00	+0.0	+00 +0.0	+00 +0.0	+00
 INITIAL TEMPERATURE IS CONSTANT					
+0.0	+00	+530.0	+00 +530.0	+00	
 <b>42</b>					
+0.0	+00	+0.0	+00 +342.9	+00 +1400.0	+00 +449.7 +00 +1800.0 +00
+617.2	+00	+2400.0	+00 +791.0	+00 +3000.0	+00 +978.0 +00 +3600.0 +00
+1113.0	+00	+4000.0	+00 +1200.0	+00 +4224.0	+00 +1300.0 +00 +4486.0 +00
+1400.0	+00	+4725.0	+00 +1500.0	+00 +4936.0	+00 +1600.0 +00 +5127.0 +00
+1700.0	+00	+5299.0	+00 +1800.0	+00 +5454.0	+00 +1900.0 +00 +5596.0 +00
+2000.0	+00	+5728.0	+00 +2100.0	+00 +5851.0	+00 +2200.0 +00 +5968.0 +00
+2300.0	+00	+6078.0	+00 +2400.0	+00 +6186.0	+00 +2500.0 +00 +6291.0 +00
+2600.0	+00	+6395.0	+00 +2700.0	+00 +6497.0	+00 +2800.0 +00 +6597.0 +00
+2900.0	+00	+6699.0	+00 +3000.0	+00 +6805.0	+00 +3100.0 +00 +6918.0 +00

TABLE I - SAMPLE PROBLEM INPUT - Concluded

(b) Fortran data card listing

+3200.0	+00+7050.0	+00+3300.0	+00+7175.0	+00+3400.0	+00+7350.0	+00
+3500.0	+00+7480.0	+00+3600.0	+00+7630.0	+00+3700.0	+00+7800.0	+00
+3800.0	+00+7470.0	+00+3900.0	+00+8120.0	+00+4000.0	+00+8300.0	+00
+4100.0	+00+8500.0	+00+4200.0	+00+8700.0	+00+4300.0	+00+8850.0	+00
+4400.0	+00+9000.0	+00+4500.0	+00+9150.0	+00+4600.0	+00+9270.00	+00

TABLE II.- SAMPLE PROBLEM OUTPUT

TYPICAL CHARRING ABLATOR - TEST CASE - 4/6/65 DONALD M. CURRY

INPUT DATA.

TIME LIMIT=6.0000E 02 INITIAL TIME=0. NPTT= 2

TIME	TIME STEP	PRINT CONTROL
0.	1.0000E-01	100
6.0000E 02	1.0000E-01	100

FCONV= 1.00000E 00 FRAD= 1.00000E 00

## TYPICAL CHARRING ABLATION MATERIAL PROPERTIES

TABL= 1.06000E 03	TCHAR= 1.46000E 03	TREC= 0.	RHOV= 3.40000E 01	RHOC= 2.00000E 01
FBLOW= 0.	EMV= 6.50000E-01	EMC= 7.50000E-01	H300= 1.29060E 02	VL= 1.50000E 00
HV= 2.50000E 02	VPT= 0.	FV= 1.00000E 00	TV= 0.	CHARK= 1.20000E-01
CHARC= 4.30000E-01	ABLK= 7.00000E-02	ABLC= 4.30000E-01		

NP= 31 NKC= 2 NCPC= 2 NKV= 9 NCPV= 2 NREC= 2

## VIRGIN MATERIAL

TEMPERATURE	CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
3.6000E 02	6.5000E-02	3.6000E 02	4.3000E-01
4.6000E 02	6.5000E-02	1.1000E 03	4.3000E-01
5.6000E 02	6.5500E-02		
6.6000E 02	6.6000E-02		
7.6000E 02	6.7200E-02		
8.6000E 02	6.8400E-02		
9.6000E 02	6.9600E-02		
1.0600E 03	7.0000E-02		
1.1600E 03	7.0000E-02		

## CHAR MATERIAL

TEMPERATURE	CONDUCTIVITY	TEMPERATURE	SPECIFIC HEAT
1.46000E 03	1.2000E-01	1.46000E 03	4.3000E-01
1.00000E 04	1.2000E-01	1.00000E 04	4.3000E-01

## SURFACE RECESSSION TABLE

TIME	SR - IN/SEC
0.	9.00000E-04
6.00000E 02	9.00000E-04

NO TRAJECTORY - Q=95 BTU/SEC-SQFT

NO. OF TRAJECTORY POINTS = 2

TABLE II.- SAMPLE PROBLEM OUTPUT - Continued

TIME	Q CONVECTIVE	Q RADIATIVE	VELOCITY
0.	7.5000E 01	0.	2.9250E 04
6.0000E 02	9.5000E 01	0.	2.9250E 04

PROPERTIES OF BACKUP STRUCTURE

NO. OF MATERIALS IN BACK-UP SHIELD= 1  
 TOTAL NUMBER OF NODES IN BACK-UP SHIELD= 3  
 THICKNESS OF BACK-UP SHIELD= 1.0000E-01

BACKUP MATERIAL 0.1 INCHES THICK

THERMAL		SPECIFIC	
TEMPERATURE	CONDUCTIVITY	TEMPERATURE	HEAT
3.6000E 02	6.5000E-02	3.6000E 02	4.3000E-01
4.6000E 02	6.5000E-02	1.1000E 03	4.3000E-01
5.6000E 02	6.5500E-02		
6.6000E 02	6.6000E-02		
7.6000E 02	6.7200E-02		
8.6000E 02	6.8400E-02		
9.6000E 02	6.9600E-02		
1.0600E 03	7.0000E-02		
1.1600E 03	7.0000E-02		

MATERIAL	DENSITY	THICKNESS	EMISSIVITY		NODES/MATERIAL
			FRONT	BACK	
1	3.4000E 01	1.0000E-01	9.0000E-01	9.0000E-01	3.0000E 00

ADDITIONAL DATA FOR INDIVIDUAL MATERIALS IN BACKUP STRUCTURE

MATERIAL	FILM COEFFICIENT	GAP THICKNESS	FTEST	BTEST
1	0.	0.	0.	0.

HEAT TRANSFER TO CABIN ENVIRONMENT - HENV=0.0

TEMPERATURE= 5.6000E 02 FILM COEFFICIENT= 0. VIEW FACTOR= 0. Q LOST= 0.

INITIAL TEMPERATURE IS CONSTANT

TEMPERATURE DISTRIBUTION IN HEAT SHIELD IS UNIFORM AND EQUAL TO 5.3000E 02

TABLE II.- SAMPLE PROBLEM OUTPUT - Concluded

## OUTPUT DATA.

TIME= 9.90000E 00 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0. VELOCITY= 2.92500E 04  
 GAS ABLATION RATE= 0. CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 5.40000E 00  
 RECESSION DEPTH= 9.00000E-03 QHOT WALL= 8.99282E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 1.00000E 01 SECONDS

## TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

3.79022E 03	2.33046E 03	1.06300E 03	6.38075E 02	5.47600E 02	5.32434E 02
5.30289E 02	5.30030E 02	5.30002E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02	5.30000E 02
5.30000E 02					
5.30000E 02	5.30000E 02	5.30000E 02	5.29999E 02	5.30000E 02	5.30000E 02
5.29999E 02					

## TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

5.29999E 02	5.30000E 02	5.30000E 02
-------------	-------------	-------------

TIME= 1.99000E 01 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0. VELOCITY= 2.92500E 04  
 GAS ABLATION RATE= 2.90720E 01 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 3.44720E 01  
 RECESSION DEPTH= 1.80000E-02 QHOT WALL= 8.99173E 01

TEMPERATURE DISTRIBUTION IN HEAT SHIELD AT THE END OF THE TIME STEP, T= 2.00000E 01 SECONDS

## TEMPERATURE DISTRIBUTION IN THE ABLATING MATERIAL

3.80935E 03	2.87678E 03	1.64575E 03	9.77202E 02	6.72698E 02	5.66204E 02
5.37857E 02	5.31496E 02	5.30254E 02	5.30038E 02	5.30005E 02	5.30000E 02
5.29999E 02					
5.29999E 02					
5.29999E 02					
5.29999E 02					

## TEMPERATURE DISTRIBUTION IN THE BACK-UP STRUCTURE

5.29999E 02	5.29999E 02	5.29999E 02
-------------	-------------	-------------

TIME= 2.99000E 01 QCONVECTIVE= 9.50000E 01 QRADIATIVE= 0. VELOCITY= 2.92500E 04  
 GAS ABLATION RATE= 1.25330E 01 CHAR ABLATION RATE= 5.40000E 00 TOTAL ABLATION RATE= 1.79330E 01  
 RECESSION DEPTH= 2.70000E-02 QHOT WALL= 8.98427E 01

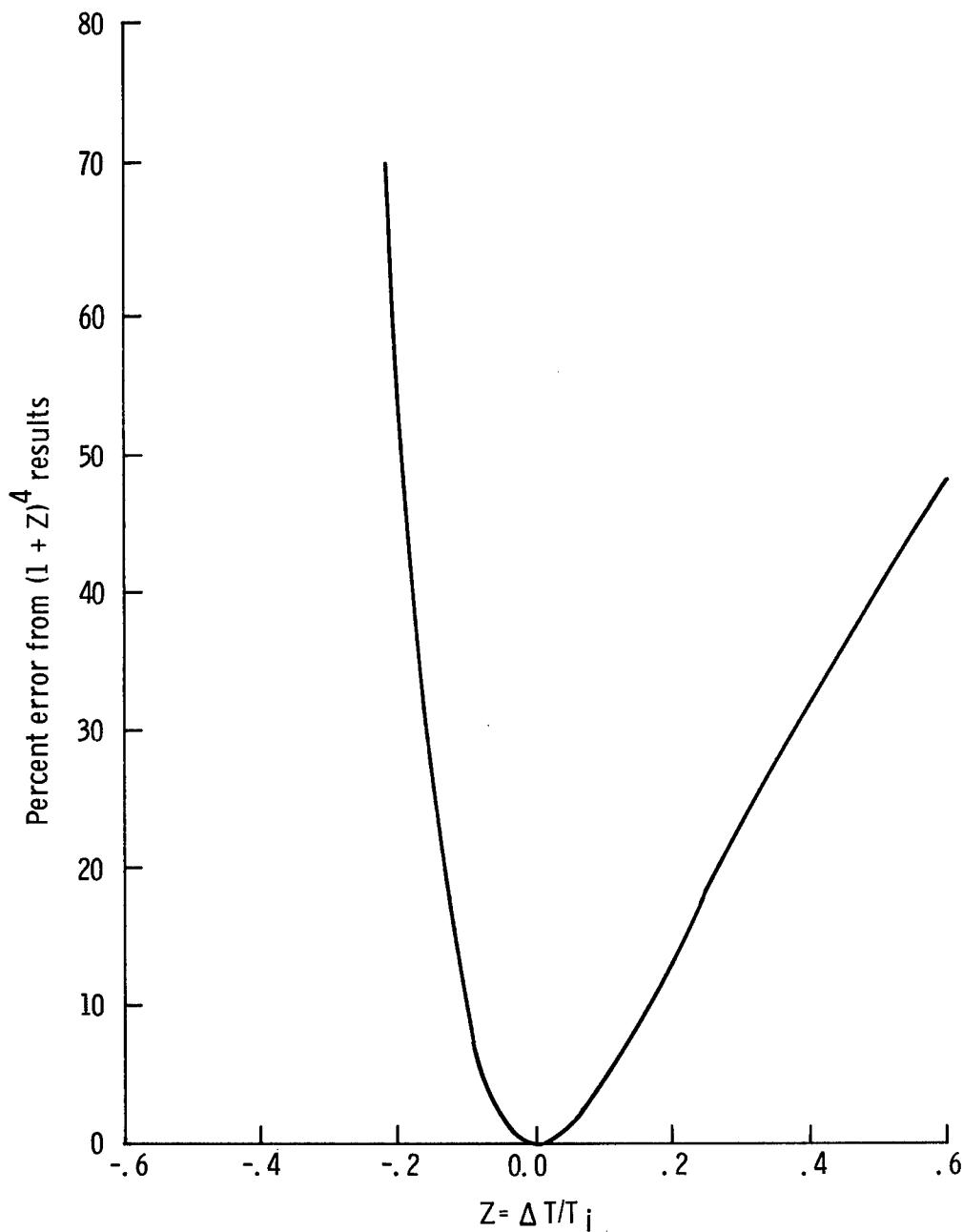


Figure 1. - Radiation temperature approximation error.

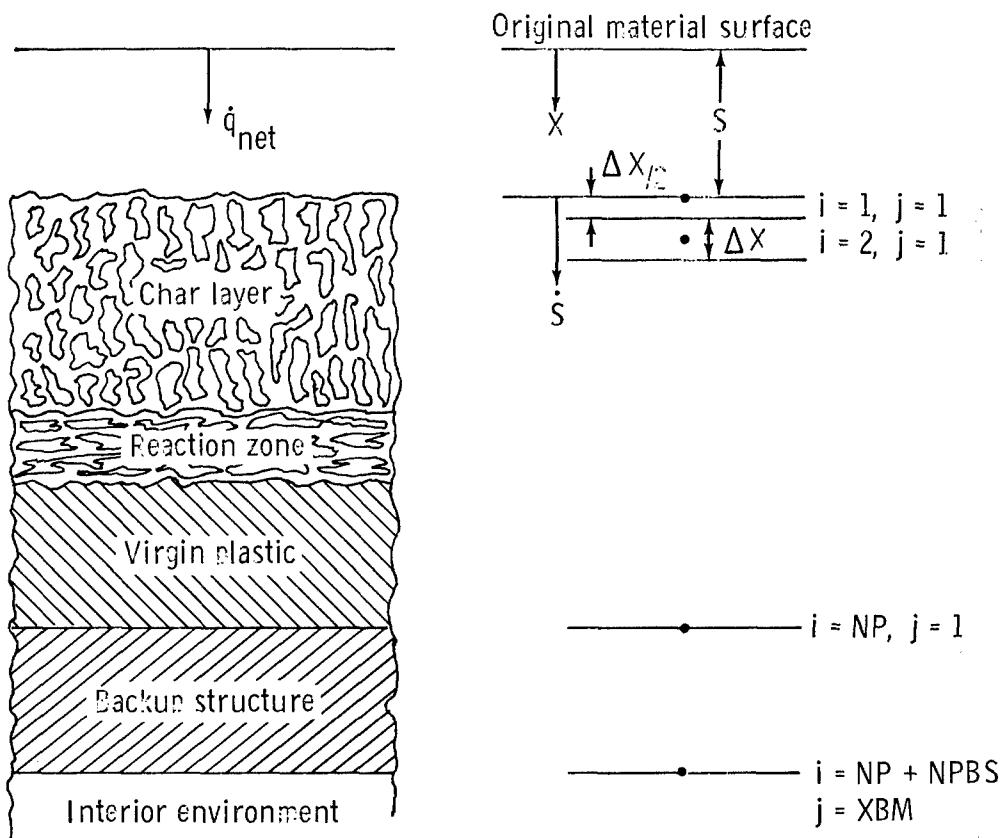


Figure 2. - Schematic diagram of charring ablator thermal protection system.

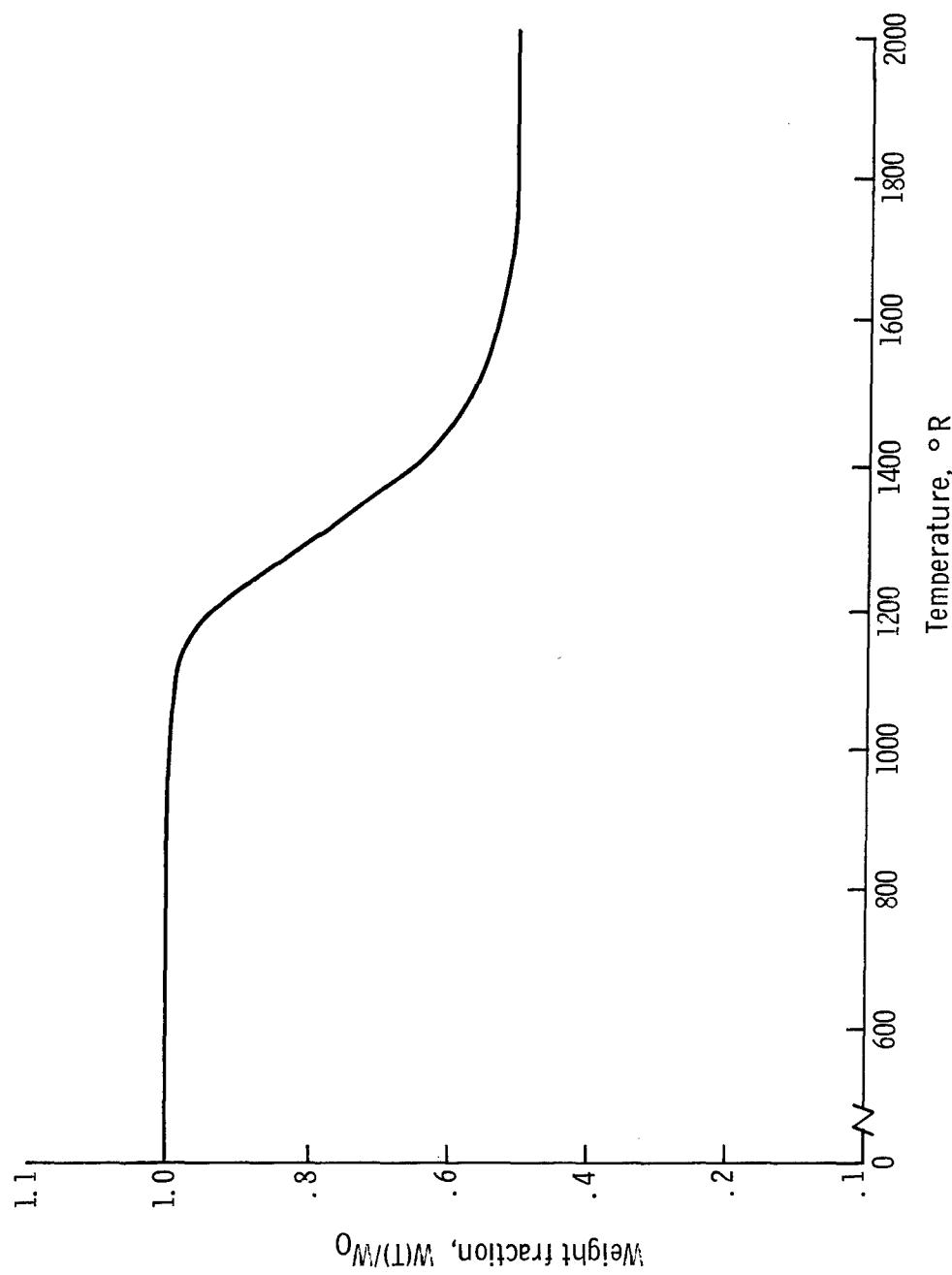


Figure 3. - Thermogravimetric data for typical charring ablation material.

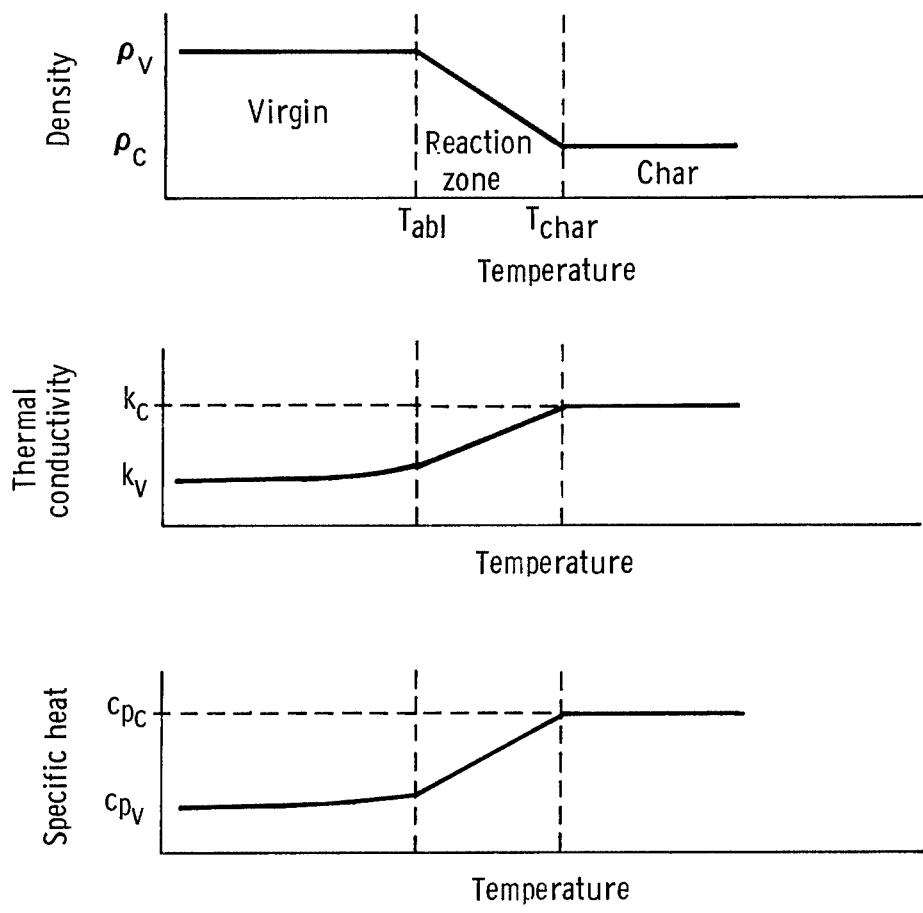


Figure 4. - Charring material property variation used as input to STAB II.

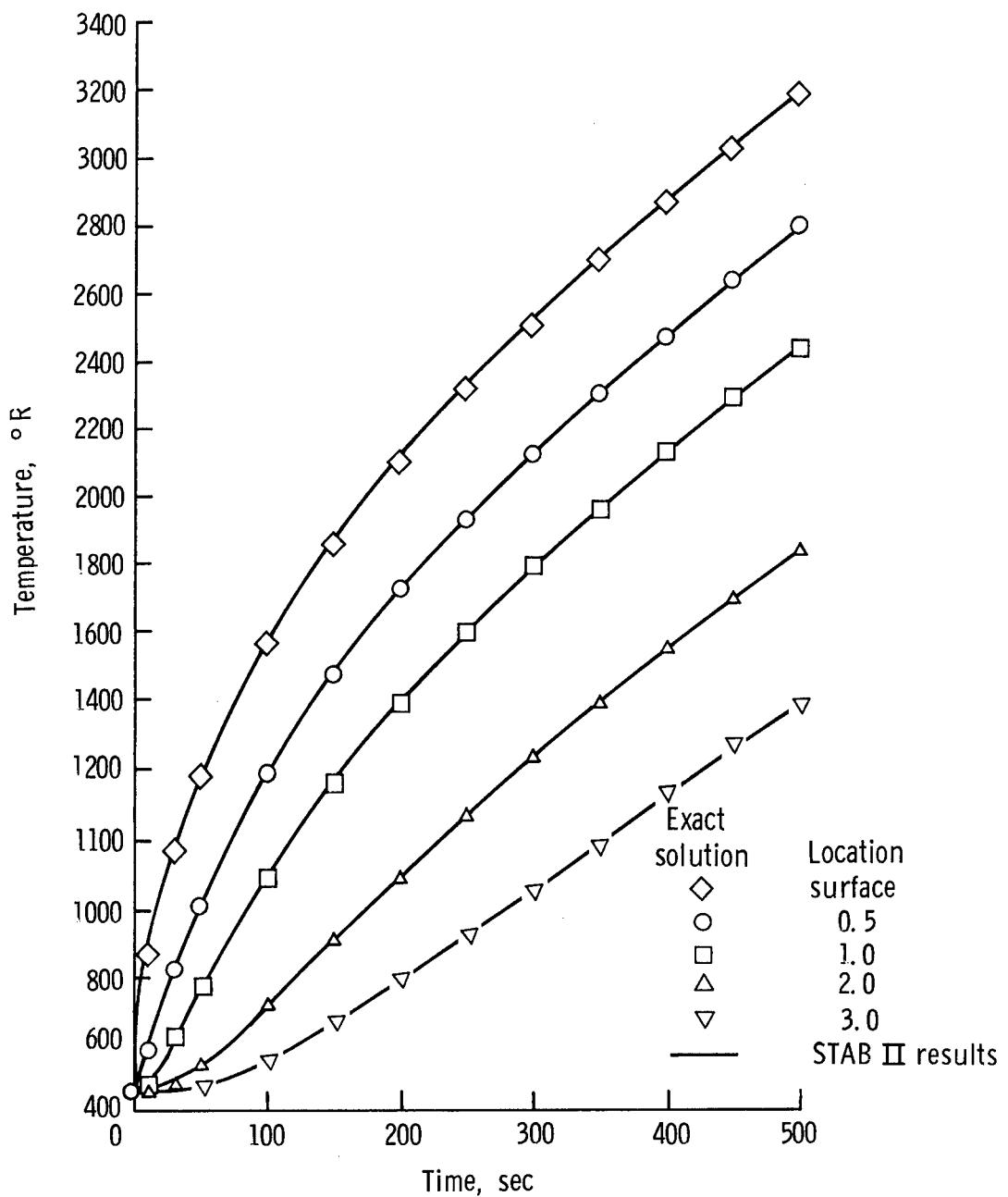


Figure 5. - Comparison of temperature histories for nonablating steel slab (pure conduction)

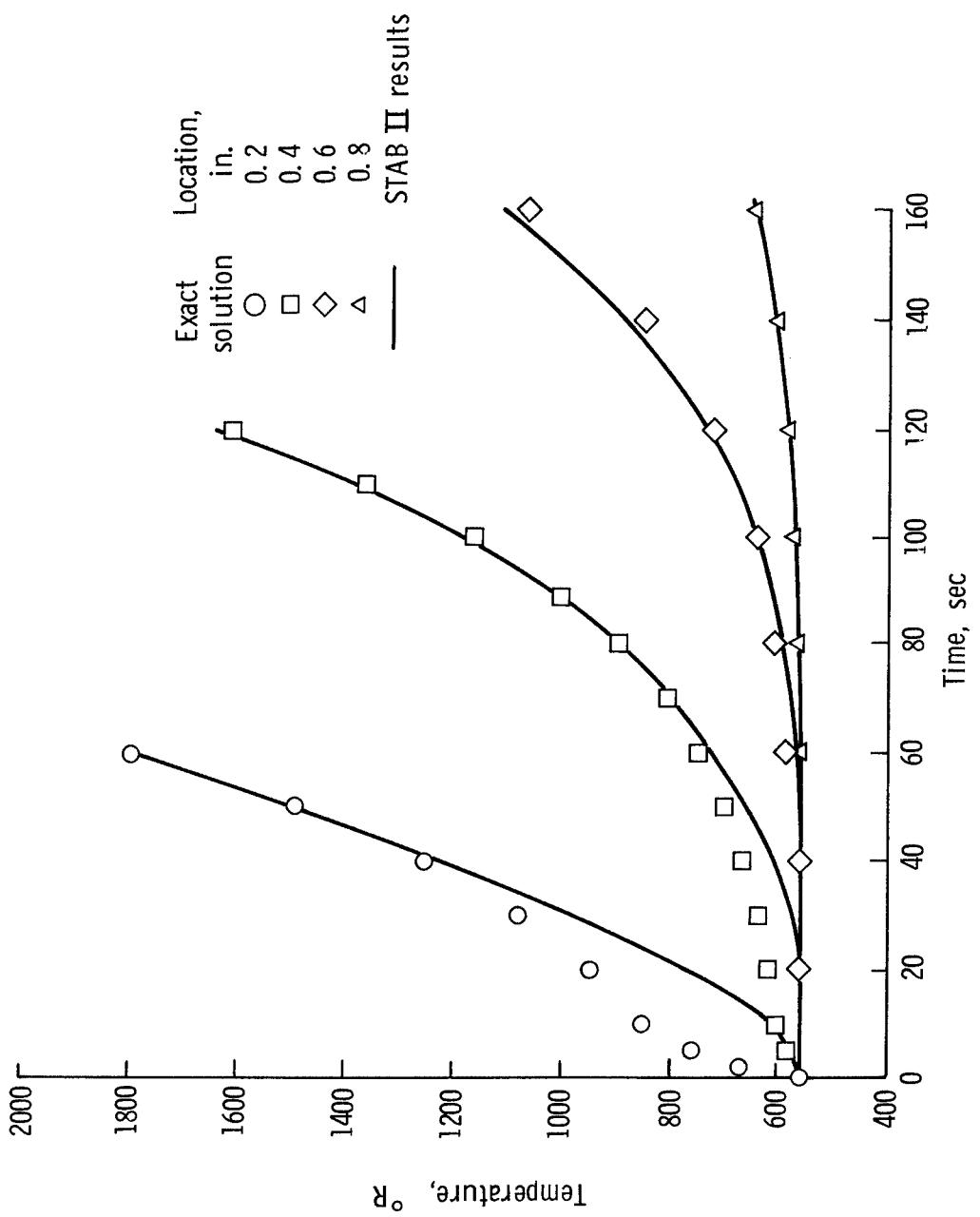


Figure 6. - Comparison of temperature histories for moving boundary model.

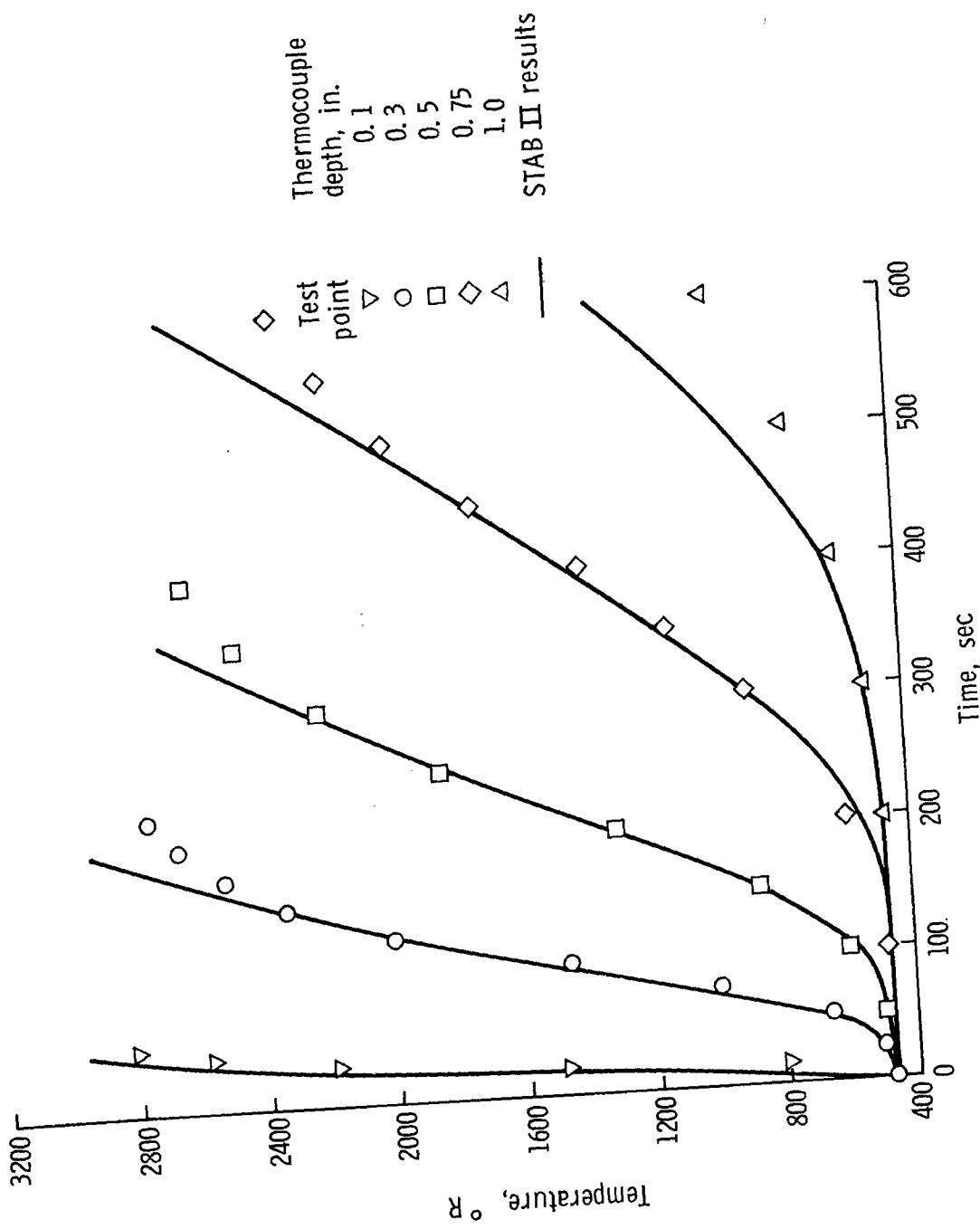


Figure 7. - Comparison of temperature histories for typical charring ablator.

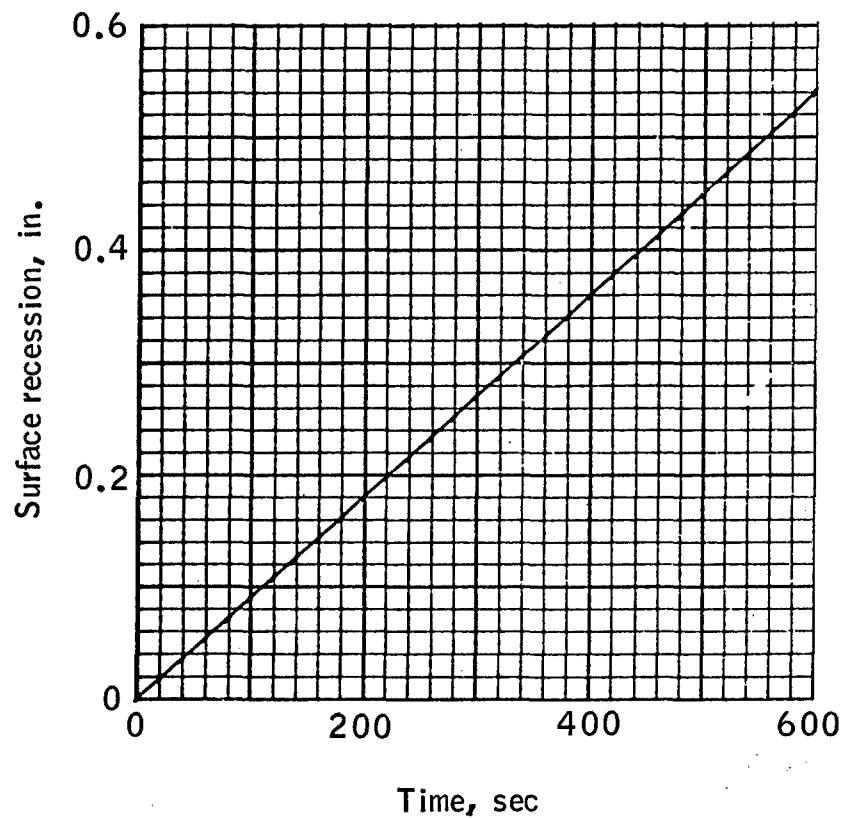


Figure 8. - Plot program surface recession curve from typical charring ablator test case.

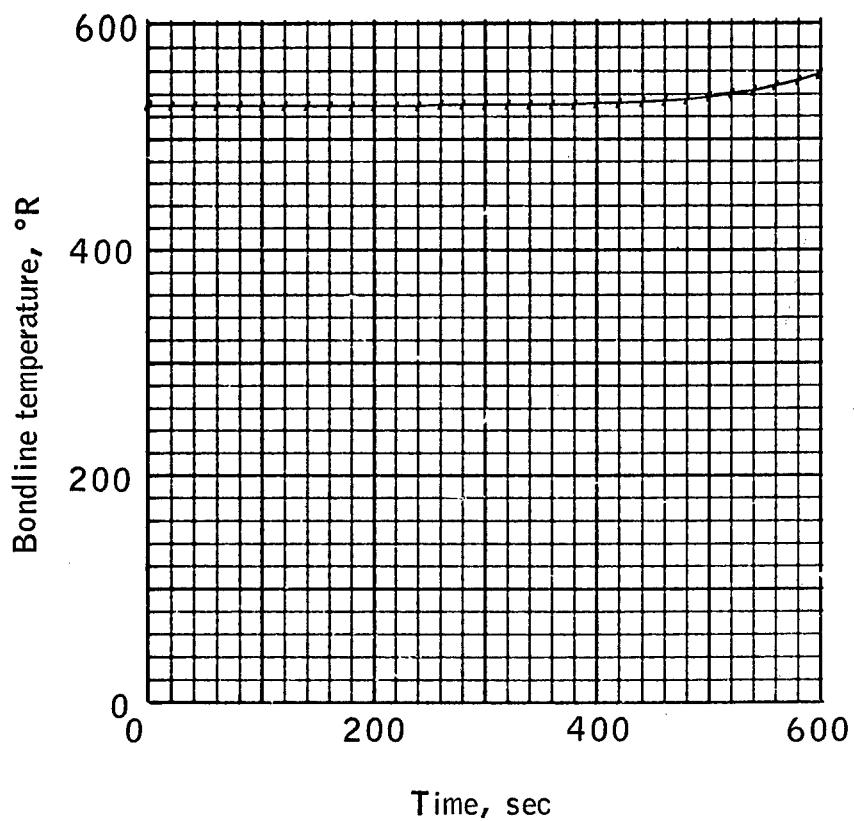


Figure 9. - Plot program bondline temperature curve from typical charring ablator test case.

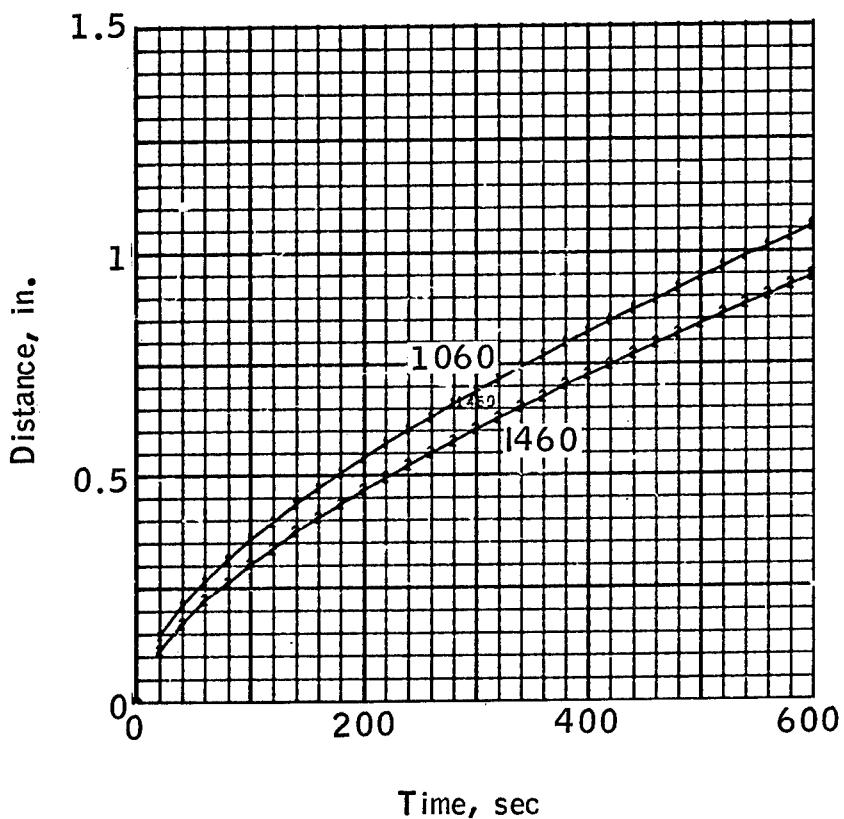


Figure 10. -Plot program 1060°R and 1460°R isotherm curves from typical charring ablator test case.